

**A STRATIFIED GIS-BASED MODEL
TO IDENTIFY OPTIMAL LOCATIONS
FOR ESTABLISHING NEW PERMANENT SAMPLE PLOTS
FOR *EUCALYPTUS BOSISTOANA* AND *EUCALYPTUS GLOBOIDEA*
IN NEW ZEALAND**

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Thai Son Le

New Zealand School of Forestry
University of Canterbury
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ABSTRACT

As part of an effort to develop a forest industry based on durable hardwood eucalypts in New Zealand, the New Zealand Dryland Forests Initiative (NZDFI) have considered *Eucalyptus bosistoana* and *Eucalyptus globoides* as two candidate species. There have been 158 permanent sample plots (PSPs) of the two species established in seven trial sites across the two main islands of the country. The network of these PSPs has provided information for the NZDFI's research program, especially for growth and yield modelling for the target species to examine the relationship between trial sites and the species (i.e. site-species matching). However, the existing PSPs do not cover the entire range of environmental conditions in New Zealand, nor do they cover the range of conditions the species are capable of growing in. Hence, the PSP network could be strategically expanded into new areas. This thesis describes a methodology, which combines habitat modelling and stratified random sampling approaches with the capability of geographic information systems (GIS), to build a GIS-based habitat model for a strategic expansion of the current PSP network.

The method applied in this study consisted of three main stages. In the first stage, the study selected 17 model variables in three categories (i.e. topography, climate, and soil), defined their importance, and tested them for multicollinearity. For each model variable, data were collected for three geographic zones: (1) the native habitat of the species, (2) all of New Zealand, and (3) the existing PSPs. The second stage was to process data to build the model. The third stage applied variable restriction and stratification analyses to calculate a priority index for the complete study area. This index represented the priority for establishing new PSPs in the study area, based on under-represented environmental characteristics.

The result chapter presents available areas for the expansion of the PSP network after the restriction process as the potential habitat for the target species. Besides excluded areas (i.e. not suitable for plantations of *E. bosistoana* and *E. globoides* in the study area), by assessing the priority index in the available areas, the result map highlighted: (1) over-represented areas (i.e. high environmental similarity, where the environmental conditions have been described by many PSPs in the existing network), and (2) under-represented areas (i.e. high environmental dissimilarity, where the environmental conditions have been described by no or few PSPs in the existing network). The results suggest that new PSPs

for the two species should be established in Rangitikei District and Taupo District. Other high-priority areas include Northland and Auckland regions, the east coast of the Gisborne region, and southeast-facing hillsides of the mountain chains in the central South Island.

Overall, the study built a stratified GIS-based habitat model that successfully determined locations for strategic expansion of the PSP networks of two different species, *E. bosistoana* and *E. globoidea*, in New Zealand. With the strengths of GIS and the availability of global GIS data, the methodology in this thesis has high potential to be applied more broadly for different species, different PSP networks, and different study areas.

ABBREVIATIONS

ALA	The Atlas of Living Australia
DEM	Digital elevation model
FSLs	New Zealand Fundamental Soil Layers
GIS	Geographic information systems
LENZ	Land Environment of New Zealand
NZDFI	New Zealand Dryland Forests Initiative
NZLRI	New Zealand Land Resource Inventory
PI	Priority Index
PSP	Permanent sample plot
TRI	Topographic Ruggedness Index
TWI	Topographic Wetness Index
VIF	Variation Inflation Factor
WEI	Wind Exposition Index

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CHAPTER 1. INTRODUCTION

Forests are a fundamental natural resource that plays a crucial role in the sustainability of nature and socio-economic development (FAO 2001). Forests have contributed to ecological structures as linked food chains in natural ecosystems, or to the availability of genetic reserves, landscapes or shelter for animals (FAO 2001). Forests have served functions such as climatic regulation, and as an oxygen and biomass source, a wood supply, a water filter, which ensure desirable living conditions for humans (Bryant et al. 1997). Because of their multifunctional roles, forest resources have been overexploited, leading to deforestation, especially in developing countries with uncontrolled cultivation and incomplete legislation for environmental and forest resource management (FAO 1990). As a result, unpleasant consequences, including climate change, biodiversity reduction, land degradation and a higher risk of local disasters relevant to water resources, have occurred on a global scale (FAO 1993; 2001).

New Zealand was not excepted when a massive natural forest area was cleared to be used as the main building material for the European settlements in the country (Boon 2005). The exploitation of native forest on public land continued until the year 2000, when it was legally banned because of adverse pressure through protests from environmental groups and nongovernmental organizations (Poole 1969; Boon 2005; McKinnon 2009). For the purposes of forest resource recovery, sustainability and its contribution to the national economy, plantation and afforestation were simply the best options (FOA 2016).

In terms of the species used in afforestation, *Pinus radiata* was introduced to New Zealand in the 1850s. It became the target species for local plantations due to its adaptability and superior growth compared with indigenous species, which were even better than its own performance in its original habitat in California, United States of America. That is the reason why *P. radiata* is now the dominant species in New Zealand and occupies roughly 89.9% of the nationwide plantation forest area (FOA and MPI 2017). Although *P. radiata* is widely adapted to New Zealand's environmental conditions and has been used for a wide range of purposes, this species only provides medium-density softwood that limits its uses. Chemical treatments, such as chromate copper arsenate (CCA), have been used in order to enhance softwood durability however they have limited export opportunities to markets that do not accept their chemical toxicity. There have been calls for New Zealand's forest industry to increase higher-quality timber products (Mead 2013; NZDFI 2017).

Another challenge for New Zealand's forest industry is to diversify the planted resource. There are opportunities to plant alternative species (other than radiata pine) in areas of the country where environmental conditions preclude optimal growth of *P. radiata*. Planting trees on the drylands of New Zealand presents a specific opportunity as, while these sites can support *P. radiata*, its growth is limited due to low precipitation and soil moisture. Drylands are areas that receive naturally low precipitation (Wilson et al. 2004; Walker et al. 2014). New Zealand's drylands are located in the rain shadow east of the main mountain ranges in both the North and South islands of this country (Figure 1.1). These areas are degrading and do not have good conditions supporting plants (Wilson et al. 2004; Walker et al. 2014). The New Zealand Dryland Forests Initiative (NZDFI), a multistakeholder project focusing on forestry research and development, has indicated that dryland landscapes require sustainable multifunctional forests that are highly adapted to dry conditions or even droughts. The multi-functional forests must yield high quality wood timber, contribute to soil erosion reduction, water quality enhancement and habitat supply for native biodiversity (Nicholas and Millen 2012).

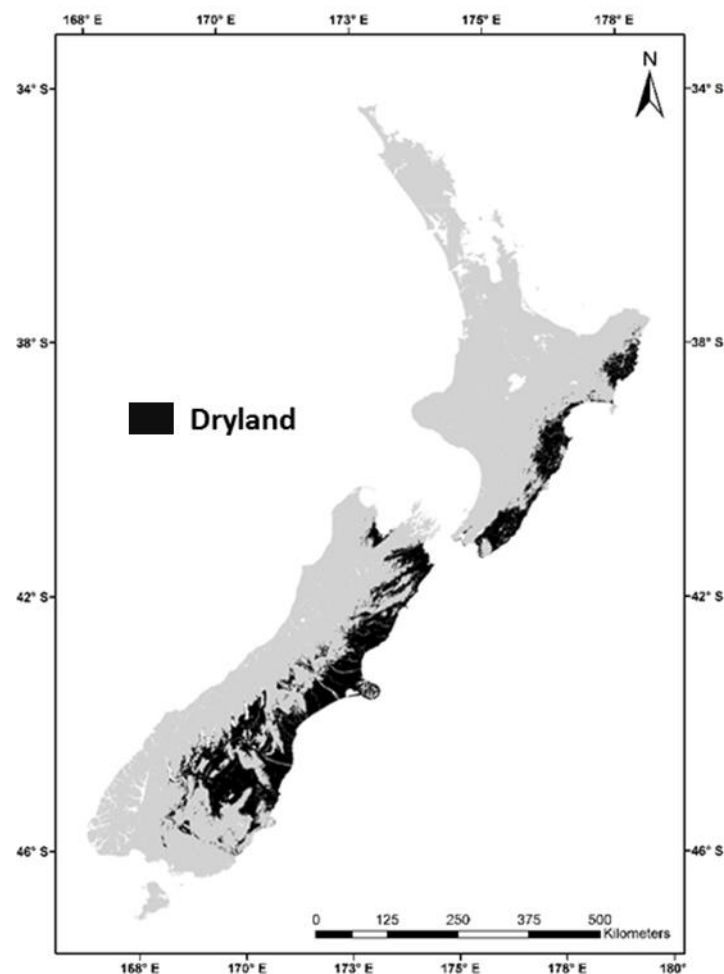


Figure 1.1. The drylands in New Zealand

One component of the NZDFI's purview is researching the potential suitability of a range of introduced eucalypt species to be cultivated as commercial plantation forests on New Zealand's drylands (NZDFI 2017). To answer the question of species selection for afforestation on New Zealand dryland, NZDFI has been looking at eucalypts which are renowned for their durability, adaptability and growth performance, not simply their ability to cope with difficult conditions such as drought, soil erosion and land degradation over hills (Adams 1981; Lyne 1996; Potts et al. 2011). They also provide shelter for nectar-feeding birds and insects as well as support for local ecosystems (Nicholas 2008; Nicholas and Millen 2012). From more than 400 eucalypts, NZDFI has selected several species to produce durable hardwood in a trial for afforestation on dryland. Those selected, including *Eucalyptus bosistoana* and *Eucalyptus globoides* seem to have high potentials for commercial forestry. One of NZDFI's study interests is where these species can be successfully established (Nicholas and Millen 2012).

For the introduction of a new plant species, site-species matching is a necessary preliminary stage to ensure the success of any plantation plan. Indeed, a new species needs to be planted on a suitable habitat that involves a set of conditions directly related to the features of the site. Typically, figuring out these conditions and their interactions and combinations is the most common approach to determine which area should be used for the plantation plan (Austin 2007). This is the reason why plantation trials need to be established before making any decision in terms of an industrial plantation strategy. NZDFI is now monitoring and annually measuring eucalypt trees in a network of more than 200 permanent sample plots (PSP) (Millen et al. 2016). However, this network is insufficient to cover all the different habitats in the entirety of New Zealand. A research priority in terms of site-species matching by NZDFI is to find the locations with environmental conditions that are under-represented by the PSP network so as to establish new plots and provide data for evaluation of the suitability of the whole country, especially drylands, for the target eucalypt species (NZDFI 2015).

For the purpose of sampling design, geographic information systems (GIS) has developed rapidly in the recent past and has also been perceived as a cost-effective approach to solve problems on broad scales, and as a powerful tool to assist decision-making processes (Bateman et al. 2002; Dimitrova et al. 2016; Mathews and Wikle 2016). Having the advantages of importing, digitizing, storing, transferring, analyzing and accessing information, both spatial and attribute (Kennedy 2002), GIS is definitely able to simulate reality with models using environmental conditions described by a number of ecological factors (Elith et al. 2006; Phillips et al. 2006). Indeed, features of a specific condition can be represented by a number of variables that are spatially packed in the form

of GIS-data layers. A series of such environmental conditions can be linked to building a system as the input of analysis for the purposes of supporting decision-making. Furthermore, following this approach, GIS-based spatial analysis has brought more applications such as species distribution prediction (Elith et al. 2006; Drew et al. 2011; Koo et al. 2015) and land suitability modelling (Roloff and Kernohan 1999; Grant et al. 2012; Basir 2014; Figueroa et al. 2017), which have high potential for the success of a plantation. These types of application consist of statistics and analyses of the various environmental factors influencing tree growth to compute the probability of successful establishment (Dettmers and Bart 1999; Store and Kangas 2001; Hirzel et al. 2006; Austin 2007).

With the capability of GIS-based spatial analysis, this research aimed to build a dataset containing a number of environmental (i.e. climatic, soil and topographic) variables to generate a model determining locations, not covered by the current PSP network, for additional PSPs establishments of *E. bosistoana* and *E. globoidea* in New Zealand. These new PSPs will ensure that all habitats for the two species on New Zealand dryland were intensively examined in the plot system by NZDFI. The characterization of these habitats is fundamental to further studies on species adaptation and species–site matching. Furthermore, this will contribute to future successful industrial plantations as well as to forestry development in New Zealand.

1.1. Background

1.1.1. Plantation forestry in New Zealand

In the past, New Zealand was entirely covered by native shrubs and woody forests until milling of these extensive forests became the major activity of European settlers in the mid-1800s in order to collect burning and building materials (Boon 2005). A huge area of indigenous forest was converted to residential areas, farmlands for livestock or left fallow (Poole 1969; Kirkland and Berg 1997).

Despite the negative impacts of deforestation identified in the Forests Act of 1874, the public awareness in terms of soil erosion and biodiversity reduction was insignificantly changed; native forest clearance continued, thus some native woody plants were recorded as threatened in 1913 (Boon 2005). The challenge facing native forest conservation led to a restriction of native wood exports by the Government in 1918. In 1925, a set of financial incentives were introduced to encourage plantation establishment with exotic species in order to reduce the pressure on native forests and the local biodiversity (Poole 1969; Boon 2005).

To ensure the success of plantations with introduced species, numerous planting trials were initially conducted involving *Pinus radiata*, *Pinus laricio*, *Pinus ponderosa*, *Pseudotsuga menziesii* and several poplars, eucalypts, and ashes. Among them, *Pinus radiata* (radiata pine) showed a high growth potential, far better than its growth in its native habitat in California. As a result, radiata pine became the main target species for the plantation forest industry in New Zealand (McKinnon 2009; Mead 2013). A large area was planted with *P. radiata* in the period from the 1920s to the 1960s, such that sufficient wood products were provided for domestic demand and also for export. This forest industry based on exotic plantation species reduced demand for native trees and indirectly protected them from extirpation in New Zealand (Kirkland and Berg 1997).

In 2016, the New Zealand forestry sector, which is predominantly based on exotic plantation forests, contributed 1.6% to GDP with planted production forests covering an estimated 1.77 million hectares. The total planted forest standing volume is 503 million cubic meters and mean forest standing age (area-weighted) is 17.1 years at April 2016 (MPI 2016b). Radiata pine is still the most important species, occupying 90% of the planted forest area, followed by Douglas fir (6%). Other species comprise the remaining 4%, with eucalypts contributing only 1% to this statistic (FOA 2016; MPI 2016b). In April 2016, the planting area of all eucalypts was recorded at 23,182 ha, in contrast with 1,532,734 ha of radiata pine (MPI 2016a).

Recently, efforts have been made to consider species other than radiata pine, with *Eucalyptus* being one of the focal genera. Changes in the net stocked area of alternative species have not yet been significant (MPI 2016b). Current research to better understand optimal sites for eucalypts, their establishment, growth and yield, wood properties, silviculture, and pest tolerance and adverse-condition resistance will help to ensure the success of future plantations.

1.1.2. Eucalypt plantations

On the global scale

Eucalypt is the name used for woody plant species in seven closely related genera including *Eucalyptus*, *Corymbia*, *Angophora*, *Stockwellia*, *Allosyncarpia*, *Eucalyptopsis* and *Arillastrum* (Lyne 1996; Carr et al. 2002; Ladiges et al. 2003). However, most global publications use this name to describe only three genera: *Eucalyptus*, *Corymbia* and *Angophora* (Lyne 1996; Turnbull 1999; Ladiges et al. 2003). ‘Eucalypt’ was first applied to naming trees in Tasmania, Australia. There have been over 700 identified eucalypt species, with more than 600 species in the *Eucalyptus* genus (Potts et al. 2011). That explains why, in the public domain, eucalypt is narrowly defined as *Eucalyptus spp.*

(Turnbull 1999; Carr et al. 2002; Bailey et al. 2012; Cancela et al. 2012). To avoid any confusion, the term “eucalypts” in this thesis specifically refers to plant species in the genus *Eucalyptus*.

Most eucalypts are naturally distributed in the Southern Hemisphere except for *Eucalyptus deglupta*. Having original habitats in Australia and several islands in Oceania, eucalypts were officially introduced to Europe via the Iberian Peninsula, Portugal in 1829 and then to several botanic gardens throughout the continent (Turnbull and Schonau 1991). Their superior adaptability and rapid growth created a strong impression on foresters when they were in cultivation. This led to a broad dispersion of this genus to other regions on the earth, such as Brazil, Argentina, and South Africa in the late nineteenth century (Eldredge et al. 1993). In the early twentieth century, eucalypts were introduced to the United States and became a reliable hardwood timber supply to complement the forest industry that was mainly based on popular softwood pine species. Eucalypts have grown in both tropical and temperate areas including more than 90 countries (Turnbull and Schonau 1991; Turnbull 1999).

At present, *Eucalyptus* has become the most preferred genus for plantations all over the world. In 2003, global *Eucalyptus* area was estimated at over 23 million ha, of which roughly 11 million ha was native in Australia and the remaining 12 million ha was plantation forest distributed in other parts of the world (Turnbull 1999; Ladiges et al. 2003). At the end of the last century, published estimations suggested that over 90% of this 12 million ha had been established since 1955 (Turnbull and Schonau 1991; FAO 1993). Tropical Asia in 1999 had about 5 million ha of *Eucalyptus* plantations, primarily distributed in India (20%); meanwhile, in tropical America, roughly 4 million ha of *Eucalyptus* plantations existed, dominated by Brazil making up to 75% of the statistics (Turnbull 1999). In Australia, 37 eucalypt species were commonly involved in industrial forestry, while 15 of them were used internationally in commercial forest plantations (Turnbull 1999).

FAO consultants (Poore and Fires 1986; Davidson 1993; Sunder 1993) have reported the advantages of eucalypts over other plantation forest species. These advantages involved ecological, economic and social positive effects:

- Great forest productivity. In other words, these species can sufficiently meet a particular demand for wood products from a smaller area (McWhannell 1960; Sunder 1993).
- Huge growth capacity and high wood density. These characteristics lead to not only wood products in massive sizes but they also have high potential to become efficient carbon sinks (Turnbull and Schonau 1991; Sunder 1993).

- Relative water-use efficiency. Eucalypt water consumption changes with the usable water availability. Most eucalypts have medium to low transpiration that can stabilize the water yield in their local area, especially on deforested or even degraded land. It is significant to the sustainability of water resource management and soil protection (Poore and Fires 1986; Davidson 1993).
- A substantial contribution to ecosystem structure. Eucalypt forests are an abundant source of shelter for animals, thus enhancing mutual relationships inside the ecosystems and promoting the richness of local biodiversity (Poore and Fires 1986; Davidson 1993; Cancela et al. 2012).
- Hardwood timber production. Several eucalypts can produce hardwood timber which is of high quality and valuable (McWhannell 1960; Sunder 1993).

In New Zealand

A long time before the establishment of extensive radiata pine plantations in the early 1920s, eucalypts had been planted in New Zealand. At that time, foresters recognized the potential for rapid growth and multi-use purpose of eucalypt timber (Judd and Menefy 2002; NZDFI 2017). In addition, sap or oil from these species could be used for medicinal purposes. For instance, western settlers collected sap from the brown gum tree (*Eucalyptus resinifera*) to use as an effective treatment for numerous common health problems such as cough, diarrhea, and fever. The species *Eucalyptus globulus* – also called “fever tree” or “Tasmanian blue gum” – was known as an antimalarial treatment (Judd and Menefy 2002).

The beginning of eucalypt plantations in New Zealand was recorded in the early 1930s; however, these plantations were on a very small scale. The individual tree planted by the Reverend James Hamlin in 1836 at Orua Bay, Auckland is believed to be one of the oldest eucalypts in New Zealand. There were no considerable eucalypt trials until the 1860s when the first eucalypt plantation was established in Greendale, Canterbury by Thomas William Adams (Judd and Menefy 2002). In the next three decades, blue gum (*Eucalyptus globulus*) was one of the preferred species choices by the government, alongside conifers and some western timbers. As a result, a number of nurseries were built in the 1880s to provide seedlings of this species for growers, with the seed source from Tasmania and New South Wales, Australia (Judd and Menefy 2002).

Unfortunately, there were formidable challenges facing the development of eucalypt forestry in the late nineteenth century. The first was extremely low temperature winters with frost; for example, in Canterbury in 1889, temperatures plummeted to -20°C . These severe conditions devastated eucalypts planted in the South Island in the early 1900s (Adams 1981). The second adverse factor was the introduction of gum-tree scale

(*Eriococcus coriaceus*) in 1908 and its subsequent outbreaks. This insect sucked sap from trees and caused a diverse range of damage, from branch dieback to mortality (Zondag 1977). These constraints, in conjunction with the success of radiata pine plantations, made eucalypts fall into disfavor; the forest industry shifted its interest to radiata pine instead (McWhannell 1960; Ball 1995).

Although eucalypt species were inferior to radiata pine in the national market at that time, they continued to be planted by farmers who grew them to provide hardwood timber for themselves. Farmers could easily grow pines, but could not provide chemical and pressure treatments for wood products to be used outdoor (Barr 1996). Therefore, eucalypts were preferred on farms due to their rot-resistance and high wood quality (McWhannell 1960). Then, in the 1970s, the government realized the strengths of eucalypts and started to raise awareness of developing a forest industry based on natural hardwood eucalypts. Considerable efforts were recorded. For example, from the mid-1970s to the mid-1980s, there was approximately 8,000 ha of eucalypt forest planted in Warkworth and Whangarei, using four species including *E. nitens*, *E. regnans*, *E. fastigata* and *E. delegatensis*. A further 11,000 ha of eucalypts were planted in Kawerau, Bay of Plenty (Judd and Menefy 2002). Eucalypt plantations have seen a resurgence, but a major challenge facing the establishment of a valuable eucalypt-based industry is to identify the species best adapted to New Zealand conditions (NZDFI 2017).

The resurrection of interest in eucalypt plantations in New Zealand is definitely understandable. Some species can produce hardwood with naturally high durability. The term “natural durability of timber” refers to “the inherent resistance of a specific timber to decay and to insect attack” (Standard 2003). In other words, timbers with natural high durability, in general, are hard, strong and long-lasting, regardless of whether they are used outdoor, above or under the ground. Hence, these durable species do not require any chemical treatment to be used effectively for a variety of end uses (McKenzie 1993; Nicholas and Millen 2012). New Zealand has planted both durable (class 1 or 2) and non-durable (class 3 or 4) eucalypts for different uses, based on the Australian Standard AS 5604 in 2003, which classified timbers by their probable life expectancies. In the current context of the rising demand for hardwood timber and prohibition against chemically treated products in some international markets, naturally durable eucalypts have become a reasonable species to add to a forest industry dominated by radiata pine. The New Zealand Dryland Forests Initiative (NZDFI) was founded in 2008 for the purpose of developing a highly competitive forest industry based on durable eucalypts. This marked a critical milestone in the deployment of eucalypt species in New Zealand (NZDFI 2017).

1.1.3. The New Zealand Dryland Forests Initiative – NZDFI

Project Vision

With a vision for 2050, the NZDFI aims to bring New Zealand to the top position among durable eucalypt breeding providers all over the world and develop a high-quality sustainable hardwood industry based on eucalypt plantations in the eastern dryland parts of New Zealand, which are dry and warm compared with the rest of the country (NZDFI 2017).

History

The predecessor of the NZDFI project was Vineyard Timbers, which was founded in 2003 by the Millen brothers, Paul and Ash, after they identified the durability of vineyard posts made from eucalypt timber and intended to use this material instead of chemically treated radiata pine. They established the first eucalypt trial plantation in Marlborough in conjunction with the local district council and landowners. For the next three years, new eucalypt seeds were imported to New Zealand to set up trials with 25 eucalyptus species to initially identify their potential. The company gained scientific support from Marlborough Research Centre and University of Canterbury's School of Forestry. In 2008, the NZDFI was officially established at the Marlborough Research Centre and attracted attention from other organizations; the first breeding generation was planted in the next year. In 2010, the project expanded to several trial bases in the North Island along with the first assessment in 2011 of the two-year-old breeding populations (NZDFI 2017). The expansion has continued until now, with a total of 30 trial sites in 7 regions (see Figure 1.2 and Table 1.1). In March 2015, at the Cawthron Marlborough Environment Awards, NZDFI won the Supreme Award (sponsored by Marlborough Research Centre Trust and Plant and Food Research) and the Business Innovation Award (sponsored by the local company Cuddon Engineering). In the same year, NZDFI also joined the Specialty Wood Products Partnership (SWPP), which was funded by the Ministry for Business, Innovation, and Employment (MBIE) in collaboration with the forest industry including the NZ Forest Growers Levy Trust, the NZ Farm Forestry Association in Marlborough and several forestry companies.

NZDFI strategy

The project's long-term strategy is to run a tree improvement program. This program is intended to set up a group of breeding populations with a prime genetic source that is large enough to provide superior seedlings for a durable hardwood industry based on eucalypts.

➤ *Species Selection*

The first task was species selection to initially identify promising eucalypts that were likely to be successfully established in New Zealand's environmental conditions. From a diverse range of species in the genera *Eucalyptus*, several high-potential species were selected as targets of the project. The basis for selecting eucalypt species was derived from:

- eucalypt populations in Australia where they first appeared
- existing eucalypt plantations in New Zealand including those that were planted by the project's predecessor in Marlborough
- research and expertise on eucalypts in Australia, New Zealand and their adaptation in other countries.

Based on the demand of the international market and the condition of New Zealand dryland, species to be selected must satisfy a set of criteria (NZDFI 2013):

- high durability (Class 1 or 2 in Australian standard)
- good growth
- good timber properties
- resistance to drought
- relatively good frost tolerance
- established timber potential in Australian and international markets.

Among numerous species performing well in earlier plantation trials and others renowned for good timber properties, the project has chosen five species as the main targets for the later breeding program (NZDFI 2013): *E. argophloia* (Western white gum), *E. bosistoana* (Coast grey box), *E. globoides* (White stringybark), *E. quadrangulata* (White-topped box gum), *E. tricarpa* (Red ironbark). Apart from these, two alternative species were also chosen as backups: *E. camaldulensis* (River red gum) and *E. cladocalyx* (Sugar gum).

➤ *Tree improvement program: Seed collection and breeding trials*

Every plantation plan needs a sufficient and sustainable source of genetic material that can provide a high probability of superior trees. Hence, there is a need to develop a rapid delivery of improved genetic materials for growers. NZDFI has operated a tree improvement program for fast-tracking the deployment of eucalypt genetic sources to be used for the foreseeable commercial forest industry and based on the selected species (Henson 2011). The program includes:

- *Seed collection*: Seeds of five selected eucalypts were gathered from different populations in Australia. This collection has ensured a rich and diverse genetic resource to

provide high-quality seedlings. Seedlings from collected seeds were propagated and deployed to different trial sites.

- *Breeding trials*: Seedlings were planted in trial sites with different conditions. Their growth has been assessed regularly to provide information for analyses of the relationship between genetic characteristics and environmental factors. These analyses are required to identify which species and genotypes are stable and superior to others, as well as their preferred specific habitats through natural selection. The probable success of these breeding trials will allow the project to achieve the overall goal by expanding the prime breeding populations in their optimal conditions in the foreseeable future.

1.2. Trial sites and the permanent sample plot network by NZDFI

The NZDFI project, essentially, is a research and development program for eucalypt forest plantations. Hence, research here is a fundamental activity in order to provide scientific information for analysis to improve knowledge and to develop silviculture techniques for eucalypt plantations in the practical situation of New Zealand. The result of these analyses will support the decision-making process.

The research program is undertaken by the NZDFI research team who focus on five main themes:

- wood quality
- tree breeding and genetics
- site-species interaction
- productivity and growth modelling
- insect pests.

As mentioned in the project's strategy, the research program has a basis of a number of planting trials with five target species. These populations are the main source of information and materials for all research activities by the program. They are compulsory for the site-species matching program because trials are the only way to know exactly which species have acceptable performance in each site, so as to make further decisions. These trials in general, or the PSPs network, in particular, are the focus of this thesis.

1.2.1. Trial sites

With support from a variety of stakeholders including farmers, vineyard owners, local authorities, forest owners and timber processors, the NZDFI has a number of trial sites in both the North and South islands of New Zealand. There are 30 trial sites established either on private or public land in seven separate regions, as shown in Figure 1.2.

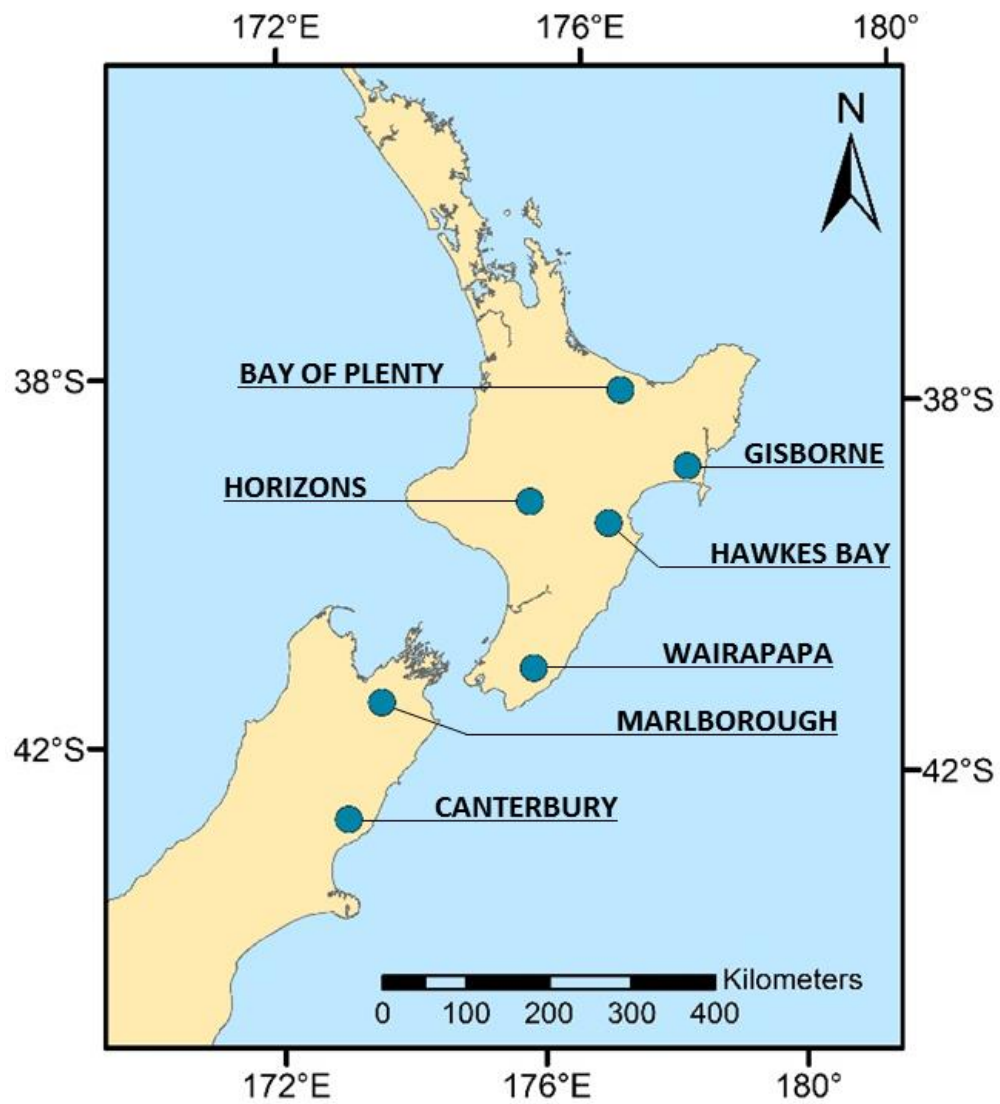


Figure 1.2. Locations of NZDFI's trial regions in New Zealand

The seven trial regions from north to south and the corresponding trial sites within them (NZDFI, 2017) are listed in Table 1.1:

Table 1.1. Trial sites managed by the NZDFI project in New Zealand

Trial region	Trial site
1. Bay of Plenty (Waikato)	1. Lake Taupo Forest Trust 2. TECT Park
2. Gisborne	3. JNL Totara 4. Wishart
3. Hawkes Bay	5. Alexander 6. HBRC 7. JNL Steeds 8. McNeill 9. Saathof
4. Horizons (Wanganui/Manawatu)	10. NZRC Okota 11. NZRC Paparoa
5. Wairarapa	12. Atkinson 13. Craigmore 14. JNL Ngaumu 15. Paton 16. Trimble 17. Williams
6. Marlborough	18. Avery 19. Clifton 20. Cuddon 21. Dillon 22. Lawson 23. Lissaman 24. Marlborough Lines 25. MDC Cravens 26. Saggars
7. Canterbury	27. Chamberlain 28. Macbeth 29. Martin 30. Phoebe

1.2.2. Trial types and the PSP network

Trial types

The NZDFI have used three main types of planting trials: progeny trial, demonstration trial, and forest permanent sample plot.

Progeny trials are sample plots planted with a single species in a particular site in order to compare and select superior individuals among that population. These individuals are likely to provide the best genetic material within a given species.

The second type, demonstration trials, include a variety of sample plots in a wide range of trial sites. Each plot is filled by a single eucalypt species for the purpose of representing the adaptation of the target species to each site and then identifying the optimal condition for that species. This type of trial is fundamental for the site-species matching program of the NZDFI.

Besides the two trial types above, forest plots are the third type of trial that NZDFI has built and regularly monitored a number of forest plots covered by eucalypt species. These plots are distributed systematically or randomly (to remove bias) among existing production forests that have been successfully established over the country. Although each forest plots usually occupies a small area, they are representative of the whole forest area where they are located.

Permanent sample plot network (PSP network)

The term “permanent sample plots” here refers to plots in all trial types (i.e. progeny trial plots, demonstration trial plots, and forest PSPs). Hence, the term “PSP network” specifies the network of all PSPs managed by the NZDFI project, which provides information for NZDFI’s research activities. This network covers a wide range of environmental conditions within New Zealand’s drylands. However, there are many remaining areas, not yet represented by any PSP, that have a high potential for further plantations. Expansion of the PSP network should be prioritized in these under-represented areas.

NZDFI is working with a total of 525 PSPs, 299 of which comprise the five target species previously described (Table 1.2). This thesis only focused on the two species *E. bosistoana* and *E. globoidea*.

Table 1.2. A description of the NZDFI's permanent sample plots

Species	Number of PSPs	Main target species
<i>E. bosistoana</i>	84	X
<i>E. globoidea</i>	74	X
<i>E. quadrangulata</i>	59	X
<i>E. tricarpa</i>	52	X
<i>E. argophloia</i>	30	X
<i>E. cladocalyx</i>	52	
<i>E. camaldulensis</i>	46	
<i>E. macrorhyncha</i>	48	
<i>E. longifolia</i>	37	
<i>E. eugenioides</i>	28	
<i>E. notabilis</i>	15	
TOTAL	525	

All the PSPs are regularly monitored, including capturing images, measuring tree survival, tree growth and measuring microsite characteristics of each site. All information collected is digitized into a GIS-based form. Each example for NZDFI's permanent sample plots is divided into a number of sub-plots to obtain more within-site variations in terms of environmental conditions, shown in Figure 1.3 and Figure 1.4. These figures represent an aerial image of various sub-plots and how digitized plots are displayed in GIS-based computer software.

NZDFI Eucalyptus demonstration trial Site 67 Saggars Established 2011

Area flown: 11/01/16

NZDFI
NEW ZEALAND DRYLAND FORESTS INITIATIVE
breeding tomorrow's trees today



Figure 1.3. Aerial photo of the PSP in Saggars trial site (source: NZDFI, 2017)

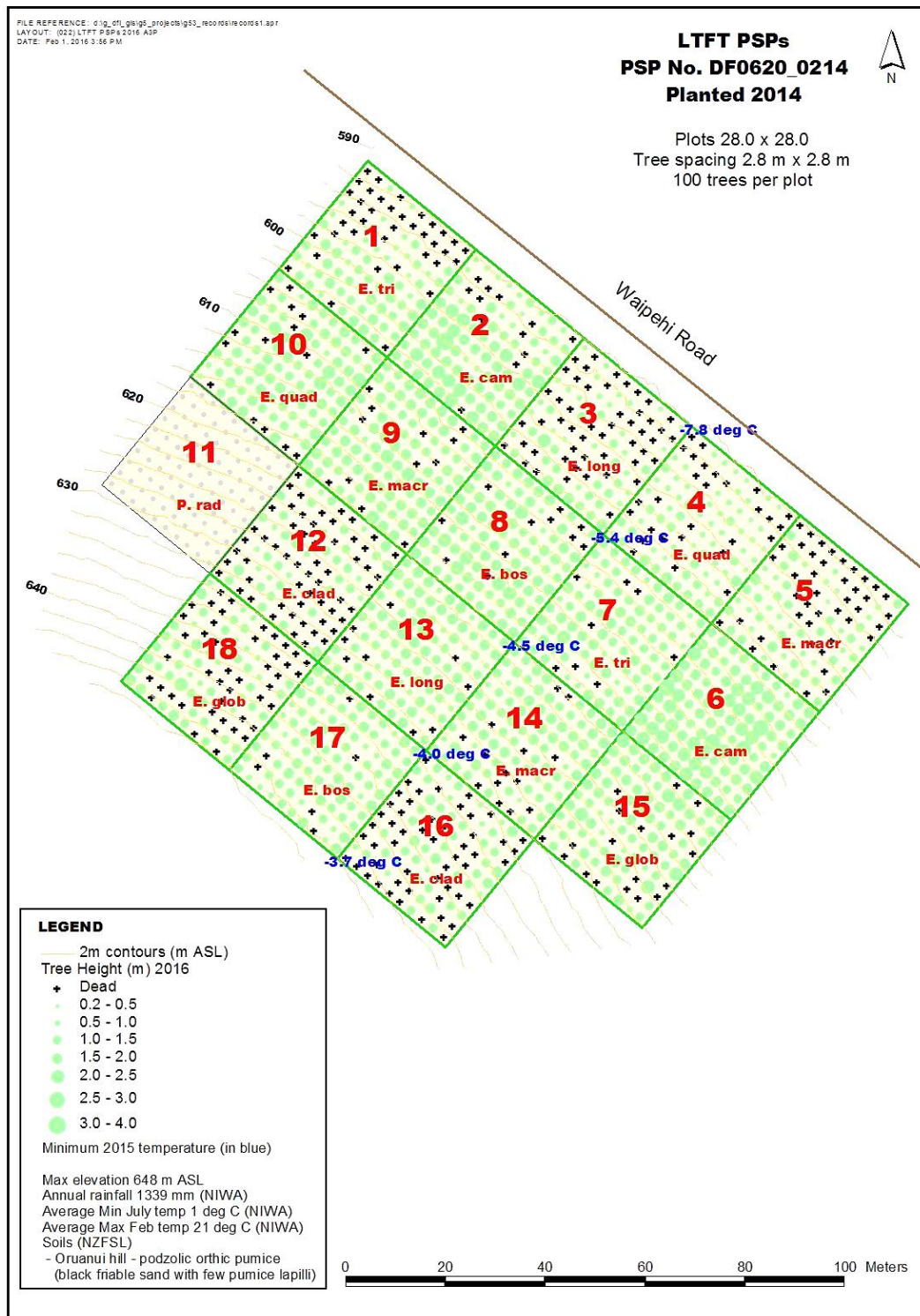


Figure 1.4. The GIS-based form of PSPs in Lake Taupo Forest Trust (source: NZDFI, 2017)

1.2.3. Limitations of the existing sample plot network

A site–species matching project usually aims to ensure that the species to be planted develops well in the plantation areas. In general, this type of project aims not only to maximize growth or other valuable traits (e.g. wood quality), but also to evaluate the influences of environmental factors and other irregular natural phenomena (e.g. frost,

snow, pests and diseases) (Caulfield et al. 1992; NZDFI 2015). Those objectives can be achieved only if the projects have a sample plot network that provides comprehensive characterizations of all environmental conditions for plantation. Characterizing a site's sample plots is necessary if we wish to identify how the local environmental condition affects tree growth and yield. This sample plot network also requires measurements each year to monitor tree growth and to assess the critical effects (e.g. mortality) of special events (e.g. frost, pests or diseases) if they occurred (NZDFI 2015).

Following the approach above, the PSP network by NZDFI has provided information for eucalypt-site matching for many years. This information is used for the necessary explanatory variables in growth and yield models; in other words, environmental conditions contribute to the explanation for measured differences in eucalypt growth and survival in trial sites. However, the PSP network is currently covering only seven sites. In addition, most of the plots in these sites are in a similar situation that they do not span the entire range of environmental conditions for eucalypt plantation in New Zealand. Successful growth models of eucalypts require a more detailed understanding of this entire range of conditions and how eucalypts grow in these situations, especially in marginal conditions.

Understanding the deficiency of the existing plots, the NZDFI species-matching project is willing to expand the plot network. However, establishing new plots in sites with environmental conditions similar to those in the current network will not support a better growth model of the target species. The new plots are required to be placed in situations that have not yet been included in the existing plot network. These new plots will provide new meaningful information for eucalypt growth and yield modelling in New Zealand.

The limitation mentioned above is also the question to the study in this thesis. I aim to contribute to an improvement of the current NZDFI plot network by identifying optimal locations for a strategic expansion of the network. The methods involve the approaches of habitat modelling and stratified random sampling, and are conducted on a GIS-based platform.

CHAPTER 2. LITERATURE REVIEW

2.1. *Eucalyptus bosistoana* and *Eucalyptus globoidea*

2.1.1. *Eucalyptus bosistoana*

Natural distribution

Eucalyptus bosistoana (common names “Coast grey box” or “Gippsland grey box”), is a species naturally found on the southeast coast of Australia (Figure 2.1). The original habitat of this species is coastal mixed forests located in areas below 500 m of elevation within a range of latitudes from 33°S to 37.5°S, in which small river flats created the most favorable conditions for them to produce the best growing performance (Boland et al. 1984). The climatic range is warm humid to cool, with a mean maximum monthly temperature of 24–29 °C in the hot season and a mean minimum temperature of 1–6 °C in winter months. With frost incidence of low to moderate level, this species can stand 5–40 frost days per year. The mean average precipitation required is 700–1200 mm a year (Boland et al. 2006).

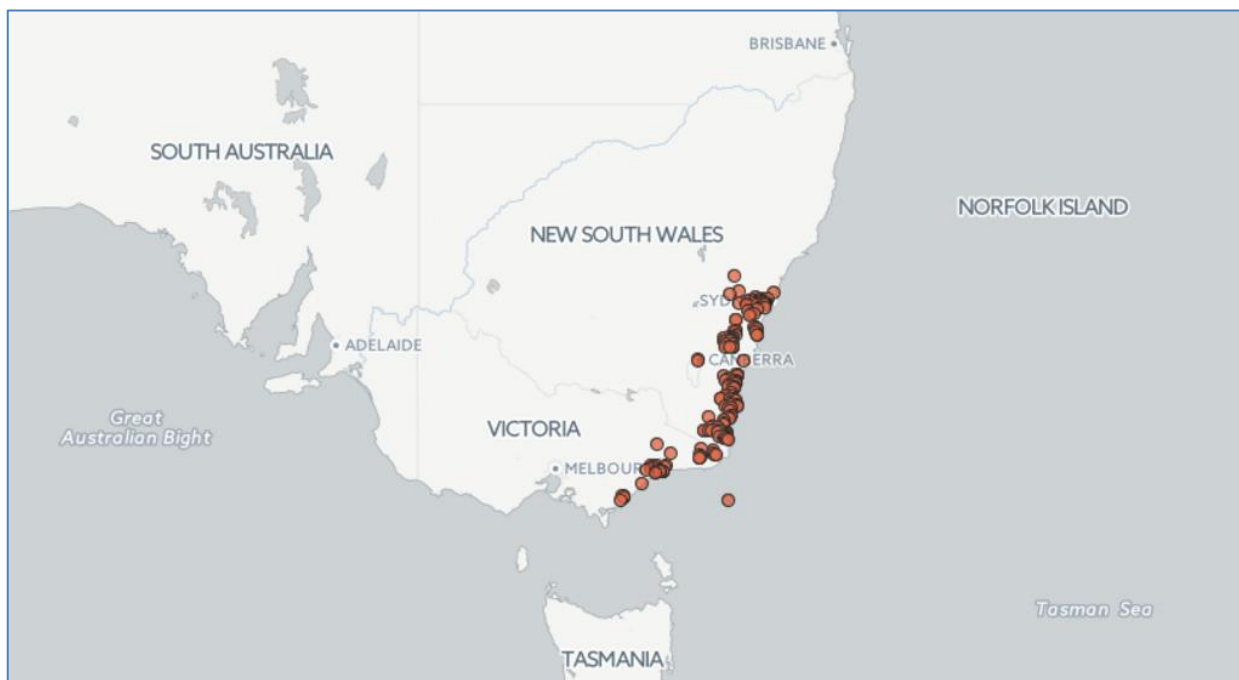


Figure 2.1. The natural distribution of *Eucalyptus bosistoana* in Australia

(Source: Australia's Virtual Herbarium, 20/4/2017)

Wood characteristics

Coast grey box has been graded as a large-sized woody species with a mean height of roughly 40 to 60 m and a diameter at breast height (DBH) of 150 cm maximum recorded in Australia. *E. bosistoana* timber is one of the hardest woods among eucalypts; it has dark

brown or pink heartwood, faded brown or pink sapwood. Due to its extremely high hardness, wood density, straightness, and durability, this type of timber has been used for numerous purposes such as farming fences, building materials, boat masts and railway ties (Boland et al. 1984; Nicholas and Millen 2012).

Status in New Zealand

In New Zealand, *E. bosistoana* was first mentioned by Simmons (1927) for its potential for timber and shelter for birds. McWhannell (1960), King (1980) and Barr (1996) also agreed with Simmons on the potential of this species if used for plantations in their sites of study, including all parts of Northland, Waikato, Hawke's Bay and Wairarapa. Data from Nicholas and Millen (2012) reported that *E. bosistoana* was successfully established in regions of Auckland, Waikato, King Country, Gisborne, Manawatu and Hawke's Bay. Small populations of this species were also found by foresters and farmers in Wairarapa, south Northland, North Canterbury, and Taranaki. The establishment probability of this species is now being tested by a number of research trials. These include trials in Para forest near Picton, on the Wither Hills near Blenheim (from 1970), also in Marlborough and Canterbury.

2.1.2. Eucalyptus globoidea

Natural distribution

Eucalyptus globoidea or "white stringybark" is an indigenous species naturally scattered across south-east Australia. A bit more broadly distributed than *E. bosistoana*, this species has been found in regions along eastern Victoria and New South Wales' east coast and tablelands (Figure 2.2). This species prefers low- to medium-slope terrains, such as slightly undulant plains and hills near the coast below an altitude of 1,100 m with warm humid to sub-humid climate. This species, with high frost tolerance, can stand more than 40 frost days per year with snow at high elevations (Boland et al. 2006).

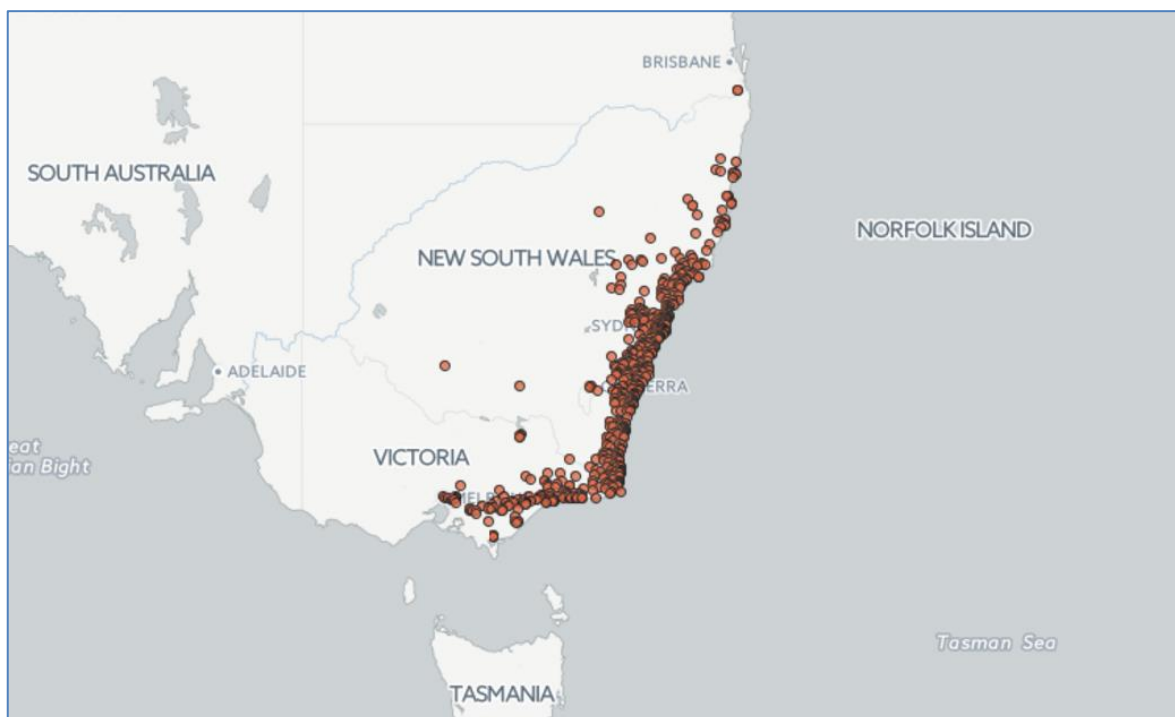


Figure 2.2. The natural distribution of *Eucalyptus globoides* in Australia

(Source: Australia's Virtual Herbarium, 20/4/2017)

Wood characteristics

White stringy bark is a medium-sized woody species with a height of 20 to 30 m; DBH is up to 1 m in favorable conditions. *E. globoides* timber appears to be pinkish-brown heartwood and sapwood. It is slightly softer than *E. bosistoana* wood; however, it is still graded as hardwood (class 1 of durability in the Australia Standard) with high density and durability and can be used for the same purposes as *E. bosistoana* (Nicholas and Millen 2012).

Status in New Zealand

New Zealand has planted *E. globoides* since the early 1900s, but on a very small scale as fragments or in mixed forests with other native and eucalypt species (King 1980); thus, it was difficult to evaluate the growth of this species in such conditions. As time went by, a fragmented *E. globoides* population has performed well in terms of growth in Little River, southern Canterbury and was described as “an impressive stand” by Simmons (1927). In addition, Weston (1957), McWhannell (1960) and King (1980) all emphasized that it was worth trying planting *E. globoides* for industrial timber production in New Zealand.

There have been several trial plantations involving *E. globoides* since the 1960s, of which a number of successful populations of this species are located in Wairarapa (Shelbourne et al. 2002), Hawkes Bay (Bulloch 1991), Manawatu (Millner 2006), the

North Island and Marlborough (Nicholas 2008), Northland and Canterbury (Nicholas and Millen 2012). These trial plantations can be the fundamental base for site–species matching activities to ascertain which variables significantly affect the tree growth and yield as well as the probability of successful establishment of *E. globoidea* as a commercial product.

2.2. GIS-based habitat modelling

To represent environmental conditions and relationships between elements inside the conditions, GIS is one of the most preferred bases due to its advantages in data management and integration with spatial analysis. The study in this thesis aims to use a GIS-based model to demonstrate the wide range of real habitats within the study area. This section initially introduces the term “environmental habitat” as well as the approach of GIS-based habitat modelling and it reviews a number of published studies that have involved GIS-based habitat modelling applications.

2.2.1. Environmental habitat

In the past, the term “habitat” had limited use. It was only used for describing an area with positive conditions (e.g. good and acceptable conditions) and good enough for an organism to live. Phrases with negative meanings in respect to habitat (e.g. unsuitable and severe habitats) were unavailable (Garshelis 2000). In other words, such phrases as “unsuitable habitat” and “severe habitat” have no meaning. If an area were unsuitable or too severe for a species to occupy, it simply was not a habitat for the species. In addition, habitat is a species-specific term. Once a habitat is mentioned, it is compulsory to clearly determine which species (or individuals of a species) are connected to the habitat.

One of the most widely adopted definitions of habitat is “an area with a combination of resources (e.g. food, cover, water) and environmental conditions (e.g. temperature, precipitation, presence and absence of predators and competitors) that promotes occupancy by individuals of a given species (or population) and allows those individuals to survive and reproduce” (Morrison and Mathewson 2015). Similarly, in biological and ecological perspectives, a habitat is an area where an organism lives and is adequately supplied with the required materials to survive and reproduce (Block and Brennan 1993; Morrison 2011). The term habitat is more often used for describing the living condition of animals because they react to a changing condition or factor more quickly and more recognizably (Morrison and Mathewson 2015).

However, Morrison and Mathewson (2015) indicated that the misunderstandings of the nature of habitat by many researchers have broadened, unintentionally, the meaning of habitat. In the expanded view, the term “habitat of an organism” refers to the surrounding environment, either natural or artificial, where the organism can exist, feed and breed

(Sutherland and Hill 1995; Muller and Kelcey 2011). Hence, the nature of habitat, in this point of view, is a mixture of factors in the living environment of an organism with less consideration than whether the organism can survive and reproduce. These factors exist together and in the same area and constitute the ecosystem. The habitat of a specific creature is usually considered in the context of an ecosystem, which also includes relationships between the creature and the environmental conditions surrounding it and between it and other creatures in the ecosystem (Morrison 2011).

More specifically, in forestry, the habitat of a particular plant species is the land where the species lives. The characterization of the land/habitat is defined as a set of both biotic and abiotic factors that influence the actual life of the species (Waring and Running 2007). For example, a tree needs resources from non-living factors such as water and nutrients from the soil, carbon dioxide from the air. The tree can be influenced by the living elements of the environments (e.g. be damaged by grazing animals and pests). Some factors exist casually in the habitat of the tree, such as winds and fires.

In this study, we focus on the definition of habitat as surroundings that affect the growth and development of a species or a population of a species. The study works with a set of abiotic surrounding factors, including soil, topographical and climatic, which compose the habitats of the target plantation species. These factors are considered as the prerequisite for further trial plantations or PSP establishments.

2.2.2. The approach of GIS-based habitat modelling

As mentioned previously, a habitat consists of a set of different factors that together have effects on the growth and development of a particular species. The most popular approach to modelling a habitat is to consider the habitat as an entity composed of a group of elements. These elements are environmental factors, and by describing them, we obtain the characterization of the habitat.

In the middle of the twentieth century, ecologists and biologists adopted a traditional approach to the method of describing a habitat (James and Shugart 1970). Following this approach, which was based on the nature of habitats composed of a set of environmental factors, there was a need for researchers to arrange a system of investigation points (or plots). Then, they had to invest considerable time and physical effort in investigating, determining and assessing the environmental conditions at all points/plots in the system. Finally, the dataset of collected data at each point/plot was used as the habitat description at the corresponding location (James and Shugart 1970). However, to entirely simulate a habitat (i.e. an area or surface), this approach required researchers to acquire data at all points within the habitat boundary; meanwhile, the number of investigated points was limited by time and labor constraints (Rice and Penfound 1955). In addition, the method to

archive data and to deal with relationships between environmental factors in the habitat also contributed to the limitations of this approach at that time (Penfound and Rice 1957; James 1978). Therefore, researchers following this approach could either assess only small-scale habitats (i.e. areas surrounding investigation points/plots) or conduct interpolation to determine habitats on a larger scale but with less reliable data.

GIS technology has the ability to store, analyze and categorize information into layers contained in datasets. Hence, GIS-based habitat modelling involves the process of representing components of a habitat as data layers and packing them together (Ferrier et al. 2002; Store and Jokimaki 2003; Hirzel et al. 2006). This approach is illustrated in Figure 2.3.

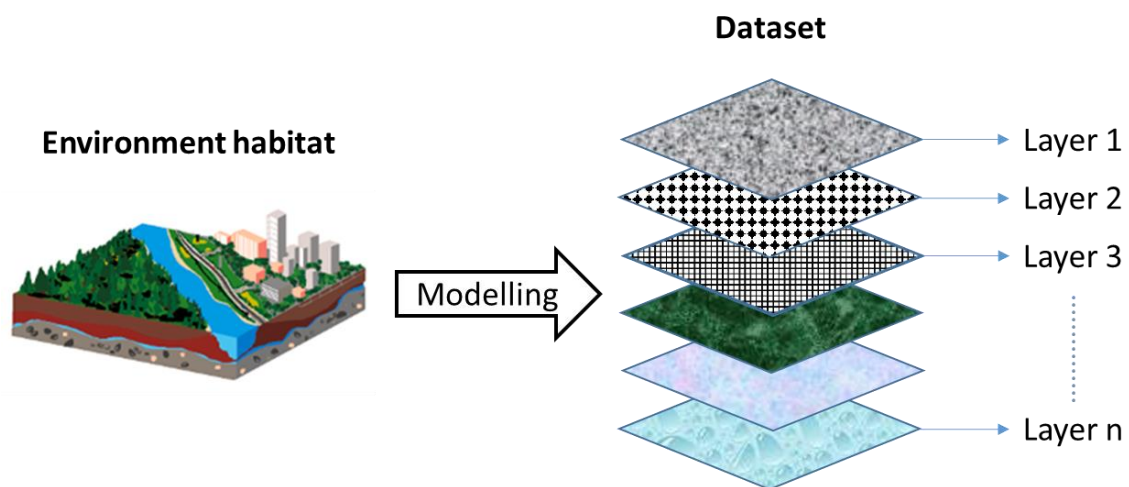


Figure 2.3. The approach of GIS-based habitat modelling

Since the foundation of the GIS-based approach to habitat modelling, the main limitations of the traditional approach have been removed. Because each habitat is an area object that contains continuous data over the surface, raster data layers are preferred for use in habitat model construction due to their advantages in describing continuous data and avoiding data gaps among each layer. The continuity of data in a GIS-based model is a great support for analyses of relationships between habitat elements (i.e. data in layers). This GIS-based model also ensures that the status of habitat conditions at every pixel is revealed by the combination of data at the same location corresponding to each point/pixel from all layers. The more layers (i.e. environmental descriptions) are included, the more precise the habitat model is (Elith et al. 2006). However, the number of data layers in the model depends on the availability of data for the habitat area (Browning et al. 2005; Comte and Grenouille 2013; Liang et al. 2014).

2.2.3. GIS-based habitat modelling applications

Habitat is a term derived from ecology and biology. This is the reason why habitat models have been mainly applied in ecology (e.g. ecological restoration and wildlife conservation) and many disciplines related to relationships between creatures and the environment in the context of their interactions inside an ecosystem. Modelling methods are extremely appropriate for plant habitats if either presence–absence or presence-only survey data or both are available (Wintle et al. 2005). Once the model of a habitat (or an environmental situation) has been built in a virtual GIS-based world, we can simulate several to many relationships within the GIS-based world to evaluate the corresponding trends and outcomes (e.g. mortality, movement, population explosion, tree growth and yield), especially from a predictive perspective.

Habitat Suitability Evaluation

The most popular application of habitat modelling is to evaluate habitat suitability for a particular species (also ecological niche modelling) (Store and Kangas 2001; Hossain et al. 2007). In this application, the requirements of the environmental conditions for a species are fitted to the species' habitat model to determine which areas in the whole habitat are suitable for the species (i.e. they sufficiently provide what the species needs). In other words, habitat suitability evaluation aims to assess species–habitat relationships. For example, Sani et al. (2016) used a model with 15 habitat variables in six categories (including land cover, water resources, soil, landscape, climate, and topography) for assessment of land suitability for multifunctional forest species. A habitat model can also classify the suitability of the habitat by orders (i.e. low, medium and high) as in the studies by Wintle et al. (2005) and Store and Jokimaki (2003).

Another example of this application is the study by Grant et al. (2012), which aimed to build a habitat model supporting *Endospermum medullosum* plantation development in the island Espiritu Santo, Vanuatu. The researchers established 200 PSPs to collect site and growth data contributing to a habitat model. Along with tree growth, they focused on site and soil characteristics such as soil depth, drainage, soil erodibility, slope and existing land use. The association of site variables with the growth of trees was correlated with a pre-existing map to estimate the area suitable (i.e. high productivity) for the species in the study area. The model in this study, which classified the study area into three main types (unsuitable; highly suitable and available; and highly suitable and potentially available due to being covered by other crops), successfully highlighted approximately 77,000 ha of highly suitable area, of which 33,000 ha was intensively cultivated.

From GIS-based habitat models, ecologists have developed many methods to reveal species–habitat relationships, in which the habitat suitability index (HSI) is the most popular (Store and Kangas 2001; Hirzel et al. 2006; Hossain et al. 2007; Kaminski et al. 2013). HSI was first mentioned in the US Fish and Wildlife Service's Habitat Evaluation Procedures (HEP) in 1980. This index (range of values from 0 to 1), which was derived from the combination of factors in a habitat, refers to habitat availability and the probability that the habitat can be favorable for the target species (Pereira 1989; Zobel 2013). Through the use of a diverse range of tools in GIS, HSI can be easily calculated in a habitat model and spatially represented as an additional map layer (Roloff and Kernohan 1999; Hirzel et al. 2006). Thompson et al. (2006) built a spatially based habitat model to determine the optimal locations for butternut (*Juglans cinerea* L.) habitats in Mammoth Cave National Park, Kentucky, USA. The surrounding conditions of 54 known butternut presences were used in association with eight topographic and land use data layers to calculate HSI based on the algorithm of the Mahalanobis Distance statistical method. The study identified 291.6 ha of areas with the most favorable conditions for butternut restoration within the study area.

In plantation forestry, habitat modelling has usually been used for selecting sites to be planted and for evaluating land/habitat suitability of a local condition to clarify whether or not it is worth investing in plantation establishment. It is remarkable that habitat modelling can significantly facilitate the development of plantation forestry (Hossain et al. 2007; Basir 2014). In this perspective, GIS-based models have been considered as the most appropriate approach because outputs are usually spatial maps showing the value of evaluation/classification suitability for each distinctive object (e.g. cell, point, and polygon) (Store and Kangas 2001; Comte and Grenouille 2013). Fei et al. (2007) determined favorable areas for American chestnut (*Castanea dentata*) in Mammoth Cave National Park, USA and produced a suitability map for the species in the study area. This study used seven variables to build a spatial model, including slope, curvature, elevation, topographic position index (TPI), slope steepness, and modified topographic relative moisture index. All these variables were derived from a 10 m-resolution digital elevation model (DEM). Similarly, the current study by Figueroa et al. (2017) assessed the suitability of the entire area of Chile for plantations of *Camelina sativa*. The assessment relied on a nationwide habitat model composed of numerous factors in three categories: climate, soil, and geomorphology. As a result, the plant species was considered to be cultivated in an area of 960,664 ha (1.3% of the national territory).

Researchers can also conduct sensitivity analyses based on habitat models, to determine the impacts of each variable on the species of interest. For example, Sellars and

Jolls (2007) built a habitat model for *Amaranthus pumilus* (a plant of the Atlantic barrier islands). They extracted topographic information from LiDAR (light detection and ranging) data and clarified that the habitat variables, which were based on LiDAR technology, could be used for habitat modelling and habitat suitability assessment. The study also evaluated topographic constraints from the variables and clearly indicated elevation as the most influential factor in the habitat of *A. pumilus*.

Species distribution/presence prediction

Habitat models have also been applied on predictions of species occurrences and distribution, especially in terms of invasive species. The theory for this approach is that the distribution of the presence of exotic species is not random. The more suitable the habitat, the higher the probability of invasive species (Hirzel et al. 2006). Any establishment of invasive species needs a suitable condition to adopt, which can be recognized by analyzing species–site relationships in a habitat model. The approach to this theory is described as a risk assessment for new incursions of an undesirable introduced species (Smolik et al. 2010; Drew et al. 2011). A habitat suitability model is developed from a habitat model for the purpose of indicating the most suitable areas for an invasive species in an area of interest. These most suitable areas thus are considered as the areas with the highest risk of invasive species being present. The effectiveness of an application in respect to plant presence prediction was assessed by Hirzel et al. (2006). The researchers evaluated presence prediction models, which were based on habitat suitability evaluation, of 114 plant species. The environmental variables in the study to fit the models were proved to have significant direct eco-physiological impacts on plant species by a number of publications. The results showed that, in general, each presence-only evaluator was fairly well correlated to the presence or absence of the corresponding species of interest and the models could be used as tools for management. Furthermore, Elith et al. (2006) reviewed and compared 16 existing GIS-based predictive models, which were built by different statistical methods (e.g. MAXENT, GARP and BIOCLIM), over worldwide occurrence data of 226 species in 6 different regions. The researchers fitted presence-only data with 13 environmental variables to build models and used an independent set of presence/absence data for model evaluation. This study showed the potential of these models using large-scale databases of occurrence data to predict the distribution of species all over the world and the potential to enhance the accuracy of species-distribution predictive models by the model combination. The potential for the application of predictive habitat models was also confirmed by Lemke and Brown (2012) who assessed GIS-based models developed by the statistical methods of either logistic regression or maximum entropy, for three alien plants at varying levels of presence. The impact of human

disturbance, spatial and temporal heterogeneity and several landscape characteristics were input as surrounding variables. The study found that the integrative model could enhance the ability of habitat modelling to predict species distribution.

Another method involving habitat modelling to predict species distribution in general and the occupancy of an alien species, in particular, is to simulate the set of conditions at the locations occupied by the alien species. All locations where pest incursions have occurred are considered as high-risk areas. The task of the modelling application is to find other locations with the same or similar conditions that can be identified by a habitat model. These locations are likely to be susceptible to the invasive species (Valverde et al. 2011; Liang et al. 2014). For instance, Liang et al. (2014) used an 11-variable spatial model to assess the invasion risks of hemlock woolly adelgid (*Adelges tsugae*) in Kentucky, USA. The model was analyzed with two statistical tools (Maximum Entropy (MaxEnt) and Mahalanobis Distance (MD)) to quantify the similarity of condition at every single pixel corresponding to the locations where the adelgid was found. The result of this study was a hotspot map indicating the highest risk areas likely to have further occurrences of the adelgid.

Change estimation and prediction

Habitat modelling is also applied in change evaluation. By building and comparing time-series models of a habitat, we can indicate the trends in how the habitat has changed. Then, following those trends, it is possible to forecast the status of the target habitat at a point of time in the future. On the other hand, a virtual model of a habitat can also be built by predicting a situation at a point in the future when the statuses of several or all elements of the habitat would have changed. Once the assumptions of habitat elements are determined, we obtain a model describing the habitat's condition at that point of time. This method of habitat prediction is significant when the environment is changing (e.g. higher temperature, lower radiation, and lower precipitation) in the context of increasing climate variations. The two applications mentioned above are used for supporting further decision-making processes. Change-detection modelling can be used to determine critical habitat areas that are degraded and need to be either protected in a conservation program or recovered in a restoration program. Another example for this application is the study by Koo et al. (2015), in which the researchers predicted the impacts of global warming on the natural habitat of red spruce (*Picea rubens* Sarg.) in the Great Smoky Mountains National Park, USA. The study created predictive models of the habitat and evaluated the corresponding changes of habitat suitability index (HSI) in three scenarios involving variations of temperature, precipitation, and air pollution. The general prediction was that

climate change was a driver of reduction of red spruce habitats at both lower and higher elevations in the study area, and the effects would be intensified by air pollution.

The review above shows that GIS-based habitat models have been widely applied for various purposes in terms of forestry and ecology. This review also revealed the linkages between habitat modelling and its main applications, as illustrated in Figure 2.4.

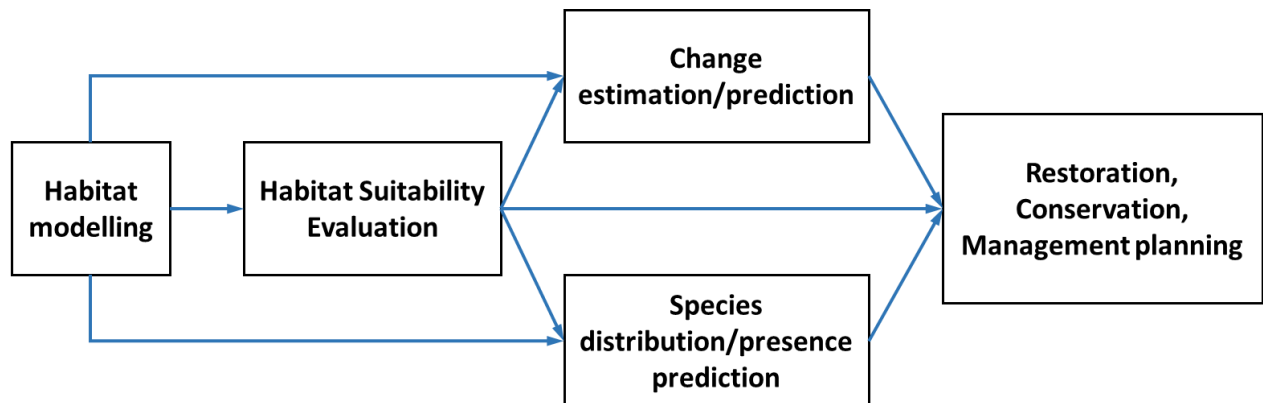


Figure 2.4. The linkages between habitat modelling and its main applications

However, there has been a lack of research in forestry using habitat modelling and spatial analysis as tools to allocate PSPs in the field. The study in this thesis aims to develop a new application of habitat modelling to optimally expand the PSP network by NZDFI.

2.3. Stratified Random Sampling

Recently, the most common way to indicate which locations are appropriate to the planting of a species is to build models that describe the relationship between environmental conditions and the growth of trees (Millen et al. 2016). Along with simulating site conditions by the combination of different environmental factors, it is necessary to acquire actual data of how trees survive and grow. This is the reason why trial plantations and PSPs must be established to provide growth and yield data such as simulations of plant development (NZDFI 2015). However, in most research on forest resources and environmental management in general, PSP systems have been built systematically or based on the spatial distribution of study objects, or even randomly (Ellis and Hayes 1997; Gobakken and Nasseta 2008; Maleki and Kiviste 2015). In such sampling methods, the range of variability of environmental factors is restricted if either the number of sample plots is too small or the study area is too large (Pielou 1984; Yves and Ecker 2014). Hence, these sampling methods require high sample-plot densities (i.e. number of plots over a unit of area) to achieve a reliably high level of sample efficiency.

In the context of a study over an extremely large area (e.g. national survey) or an isolated area that restricts the availability of sample plot establishments, stratified random sampling is a preferred solution for cost-effective sampling design (Esfahani and

Dougherty 2014; Tomppo et al. 2014; Yves and Ecker 2014). Following this sampling method, the sampling frame is classified into non-overlapping groups or strata by a particular distinct characteristic (e.g. distribution, spatial area, and age). Then, a number of samples are randomly obtained within each group or stratum. In stratification, samples from the same group are similar and the variability of samples in terms of the characteristic of interest is well represented by the number of strata. Hence, stratified random sampling will more accurately reflect the range of sampling data variability compared with other methods that are totally random without any orientation (Neville and Sidney 2001; Esfahani and Dougherty 2014). For instance, in a study by Huebner (2007), four sampling methods, including systematic, stratified random, modified Whittaker and timed meander, were compared in a case study of the detection and monitoring of exotic invasive plants in hemlock and red oak forests. The conclusion was that the stratified random method significantly detected invasive plant species and was able to determine the richness, abundance, and diversity of the species.

Another advantage of the stratified random sampling method was shown by Wallenius et al. (2011) when the researchers compared two sampling methods, stratified random and simple random, to estimate the mean and spatial variation of soil microbiological properties. Indeed, the example in the study showed that stratified random sampling reduced the required number of samples by up to 40% compared with simple random sampling. As a result, the requirements for labor efforts, budget and time were also reduced without loss of precision. This is why this sampling method has been widely adopted in other studies involving cost-effective sampling design (Niklitschek and G. 2011; Freeman et al. 2012).

In the areas of ecology and forestry, there have been numerous studies using stratified random sampling as a segment of methodology for a variety of different purposes, especially for sampling design. In addition, strata are usually defined on the basis of environmental variables that influence the target object of sampling (i.e. animals, plants, and ecosystems). For example, Knollova et al. (2005) applied this method to select representative samples from a phytosociological database of 6050 sample plots on mesic grassland in the Czech Republic. The researchers designed and compared many strategies for stratification; each strategy used a single feature to stratify the database (e.g. geographical location, habitat category in a GIS model and traditional habitat classification). The conclusion of the study was that stratified random sampling increased the representativeness of samples but different options of stratification resulted in dissimilar levels of effectiveness. The study also emphasized that the term “optimal

stratification” had no meaning in that situation and the appropriate stratifying option must be based on the specific purpose of sampling in a particular study.

Stratified random sampling has been considered as a basis for sample plot allocation. This method enhances the ability of a sample plot system to represent the entire range of desirable data in the area of interest (i.e. the study area which the plot system covers). For example, Yves and Ecker (2014) developed a complex national sampling design that was mainly based on stratified random sampling. This design contained permanent sample plots of protected dry grasslands targeted by the national inventory of Switzerland. The characteristics of interest for stratification in this study included biogeographical region, vegetation type, and spatial distribution. As a result, the developed design of plot allocation met all requirements in terms of data representativeness, investments in field-work and travel time, accessing constraints and the balance of total plot area between defined strata. In another study by Tomppo et al. (2014), the stratified random sampling method was applied to create an efficient sample plot system design for the national forest inventory in Tanzania. Sampling errors and the field measurement costs of the inventory, which were estimated by a sampling simulation, implied the potential success of the designed plot system.

As a result of those examples reviewed above, this thesis selects stratified random sampling as the method to allocate additional PSPs to expand the plot network. All environmental variables are stratified as characteristics of interest. This ensures that the plot network after expansion can reflect the complete range of habitat conditions for the two target eucalypts in the study area.

CHAPTER 3. GOALS AND OBJECTIVES

3.1. Overall goals

This study's overall goals are to develop contextually appropriate methods to (i) determine locations optimal for the establishment of new permanent sample plots (PSP) of *E. bosistoana* and *E. globoidea* in New Zealand that enhances the effectiveness of the current PSP network; and (ii) contribute to the long-term development of the plantation forest industry in New Zealand and to a new basis for permanent sample plot allocation in scientific research.

3.2. Objectives

The specific objectives to achieve the above goals are to:

1. Establish a dataset of environmental variables as a habitat simulation for the species in the study area;
2. Identify stratified gaps of environmental characteristics from the dataset that are not represented by the land on which existing PSPs are situated;
3. Indicate and highlight optimal locations for additional *E. bosistoana* and *E. globoidea* PSPs in the study area on a priority index map.

3.3. Outcomes of the research

1. A set of data layers of fundamental variables for the model;
2. A set of strata in each variable with corresponding standardized priority index values that indicates whether the environmental conditions were well covered by the existing PSP networks of *E. bosistoana* and *E. globoidea*;
3. A map that represents identified locations for new PSP establishment.

CHAPTER 4. METHODOLOGY

4.1. Study area

The study area to be simulated includes the two main islands of New Zealand, which covers a total of roughly 268,000 km², as shown in Figure 4.1. This region has terrain that is mainly steep or undulant with a wide range of topographic and climatic conditions (i.e. elevations ranging from sea level to 3737 m above sea level (Barringer et al. 2002), annual average temperatures ranging from -2.55°C to 16.79°C and annual precipitation ranging from 392 to 6807 mm/year (source: WorldClim Version 2 by Fick and Hijmans (2017)). There have been numerous locations planted with *E. bosistoana* and *E. globoidea* as trial plantations or for experimental cultivation. The PSPs within these stands have been considered as parts of the PSP network (Figure 4.1).

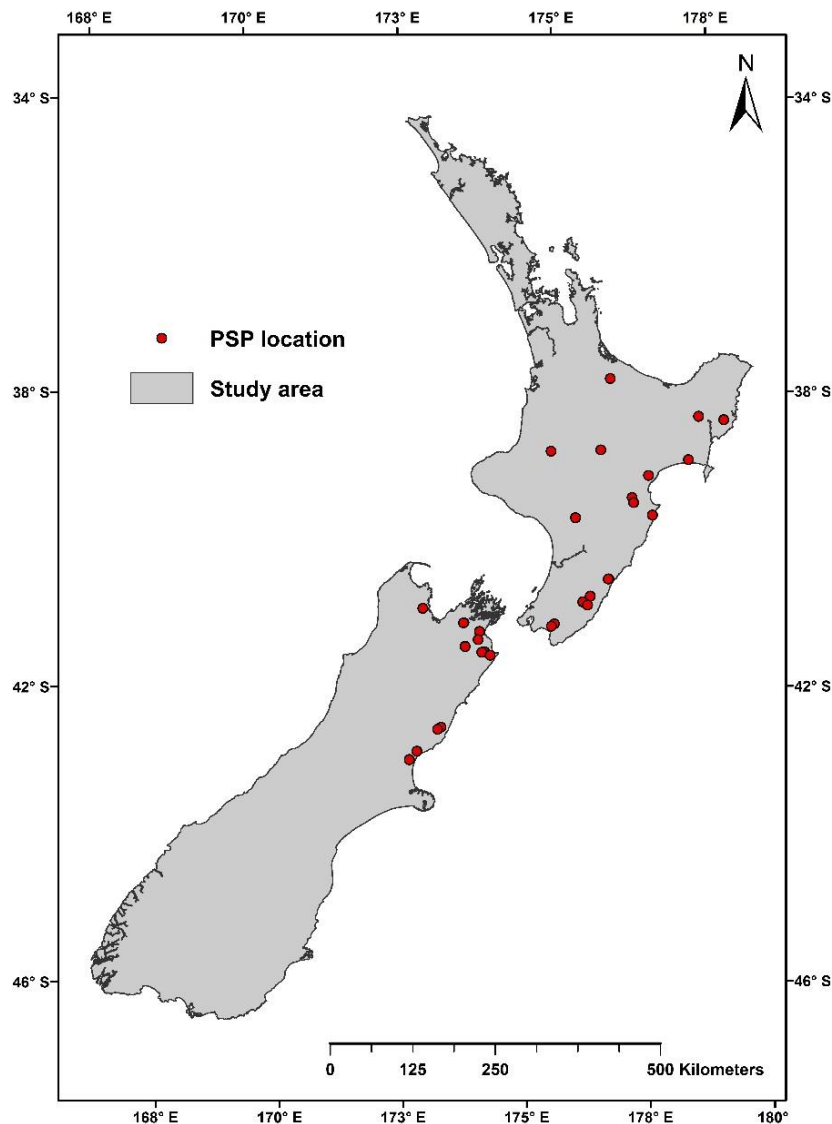


Figure 4.1. The study area and existing PSP locations (source: Statistics NZ, 2017)

4.2. Methods

4.2.1. The general outline

There have been a certain number of environmental factors (i.e. climatic, soil and topographic factors) influencing the growth and yield of *E. bosistoana* and *E. globoidea* (Prober et al. 2016), which were typically linked to habitat features. In this study, data of these factors were used to build a dataset or a simulation representing different environmental conditions in locations covered and uncovered by the existing PSPs network. The locations with characteristics out of the habitat ranges of the two target species had to be excluded by the restriction process before all variables making up the simulation were stratified without modifying the variability of values in each variable; each stratum contained a range of values that represented a distinct characteristic of the variable. Data corresponding to each variable from established PSPs were extracted and then assigned into defined strata to count their frequencies. The study assessed stratum frequencies to identify gaps in each variable that showed off the under-represented environmental variables in the PSP system. The gaps from all variables were standardized into point values (i.e. standardized priority values, ranged from 0 to 100 points) and then were combined to create an index (i.e. priority index). Using this index, the areas with conditions under-represented by the PSP network would be determined.

In more detail, the priority evaluation procedure consists of the six main steps summarized as follows (Figure 4.2):

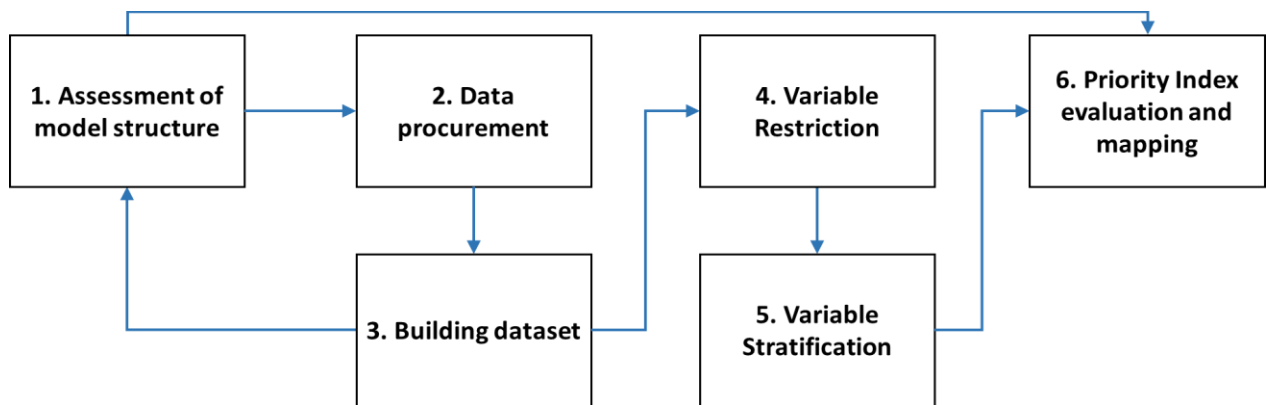


Figure 4.2. The procedure of priority index evaluation

1. Assessment of model structure: selecting model variables (e.g. temperature and precipitation) as criteria for evaluation, testing multicollinearity to remove redundant information in variables for consideration, determining their importance (allocating weight coefficient) to the priority of new PSPs in the current strategy;

2. Data acquisition: adopting study area boundaries, area units, and land cover maps; collecting raw data of modelling variables; extracting information from existing PSPs and occurrence data of the target species;
3. Building the dataset: processing all variables to create appropriate GIS raster layers;
4. Variable restriction: excluding areas with land cover unsuitable for forestry purposes, setting restriction as ranges of interest and masking out all areas with values outside these ranges (unlikely to be suitable for the species), thereby excluding those areas from further analysis;
5. Variable stratification: defining strata for each variable;
6. Priority index (PI) evaluation and mapping: assigning data extracted from existing PSPs into defined strata to calculate the standardized priority value for each stratum; reclassifying variable layers by replacing values in strata by the corresponding standardized priority values; and then weighted overlaying for PI mapping;

The output map showed the patterns of priority index over the study area. Methods applied in order to carry out the procedure above are described in detail in the next sections.

4.2.2. Assessment of model structure

Following the approach that the habitat of a species can be modelled by various environmental factors, the first step in building a habitat model is to identify which types of factors influence the growth and yield of the target species and then to select which factors in each type can contribute to the model structure as variables. This assessment depends on the species ecology and adaptability, the availability of plantation sites and the situation of further PSP establishment. In respect to forestry, the main types of natural environmental factors usually include climate, soil, and topography (NZDFI 2015).

According to the studies by Apiolaza et al. (2011) and Prober et al. (2016) in association with advice from an expert on eucalypts in New Zealand¹, and based on the available sources of data, the study has selected 17 factors (detailed in Table 4.1) as variables in three categories for the dataset, including:

1. Climate (05 layers)

- 1.1. Annual average temperature
- 1.2. Average monthly minimum temperature of the cold season
- 1.3. Average monthly maximum temperature of the hot season
- 1.4. Precipitation
- 1.5. Monthly precipitation of the dry season

¹ Dr Euan G. Mason BSc (Forestry), PhD; E-mail: euan.mason@canterbury.ac.nz

Postal address: School of Forestry, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

2. Soil (05 layers)
 - 2.1. Potential rooting depth
 - 2.2. Soil pH
 - 2.3. Soil salinity
 - 2.4. Soil temperature regime
 - 2.5. Profile available water
3. Topographic and derived variables (07 layers)
 - 3.1. Elevation
 - 3.2. Slope
 - 3.3. Aspect
 - 3.4. Curvature
 - 3.5. Terrain Ruggedness Index (TRI)
 - 3.6. Topographic Wetness Index (TWI)
 - 3.7. Wind Exposition Index (WEI)

It is important to appreciate that factors other than the 17 identified could contribute to the growth of the target species, however, the 17 identified factors had corresponding national-scale data, such that they could be readily used in modelling.

After variable selection, a multicollinearity analysis was required to test the correlations between two or more variables in each of the three categories, especially between topographic variables when they included elevation and derived variables calculated from the digital elevation model. Multicollinearity problems, if they occur, can cause overlapping significance of correlated variables in the model as well as biases to the evaluation (García et al. 2014). This problem needed to be solved by removing the overabundance of information (i.e. using only one of the violating variables with high correlations) before running the model. Variable data from the built dataset were extracted to all existing sub-plots and then were used in the multicollinearity analysis. The analysis was conducted by a Variation Inflation Factor (VIF) assessment after all the variable layers were created (Kutner et al. 2003; García et al. 2014). VIFs of all variables were calculated following the function described by Kutner et al. (2003):

$$VIF_i = \frac{1}{1-R_i^2} \quad \text{Equation (1)}$$

where VIF_i was the variation inflation factor of the variable i ; R_i^2 was the coefficient of determination of variable i (i.e. the proportion of the variance in the variable i that was predictable from the other independent variables), which was obtained by regressing the variable i on the remaining variables. VIF values equal and closed to 1.0 indicated that the independence between independent variables was absolute. VIFs exceeding 5.0 might need

further consideration, while VIFs of more than 10.0 were signs of serious multicollinearity requiring correction (Kutner et al. 2003; García et al. 2014).

The next step was to determine the importance of each variable according to its effects on the growth and yield of the species or based on an existing strategy as well as the focus of further studies using the new PSPs to be established. For example, in a project evaluating the salt tolerance of a species, variables relevant to environmental saline conditions such as soil salinity and electrical conductivity of water (Grieve et al. 1999; Lee et al. 2003) should be the most important. The importance of habitat factors was determined using a weight coefficient corresponding to each variable. In this assessment, information from published studies, judgments by experts and the availability of variable data contributed to the decision-making process. The expert on eucalypts¹ also contributed to the assessment process by identifying the environmental factors with significant impacts on the survival and growth of the species and estimating the weight coefficients for these factors.

According to the knowledge from the eucalypt expert, as well as the results from initial research on the NZDFI project, the study considered four variables as the most influential factors on the target species, including *annual average temperature*, *precipitation*, *soil pH* and *elevation*. These variables were given the weight coefficient of 1.5 in the final priority evaluation, as opposed to weight coefficients of 1, which were assigned to all other variables.

4.2.3. Data procurement

To create selected variables, raw data of variables were collected from various reliable online sources. Moreover, boundaries, territory units and land covers of the study area were provided by Statistics New Zealand, New Zealand Landcare Research and Land Environment of New Zealand (LENZ).

All PSPs in the study area belonged to the NZDFI site-species matching project. In particular, there were 1095 sub-plots from 84 PSPs of *E. bosistoana* and for *E. globoidea*, there were 837 sub-plots from 74 PSPs. The study also adopted occurrence data of the species from Australia where they naturally appeared. There were 1,598 occurrences of *E. bosistonana* and 12,101 occurrences recorded for *E. globoidea*. These occurrences and their locations contributed to the foundation of the native habitat definition for the target species.

The summary of data procurement is shown in Table 4.1.

¹ Dr Euan G. Mason, BSc (Forestry), PhD, Associate Professor. E-mail: euan.mason@canterbury.ac.nz
Postal address: School of Forestry, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

Table 4.1. GIS raw data used for habitat modelling

Category	Raw data	Unit	Source	Data type	Resolution
Climate	Monthly mean temperature (12 layers)	°C	WorldClim Version2 (the average for the years 1970-2000)	Raster	1 × 1 km
	Monthly minimum temperature (12 layers)	°C			
	Monthly maximum temperature (12 layers)	°C			
	Monthly precipitation (12 layers)	mm			
Soil	Potential rooting depth	m	New Zealand Fundamental Soil Layers (FSLs)	Vector	N/A
	Soil pH	N/A			
	Soil salinity	%			
	Soil temperature regime	Classified (*)			
	Profile available water in soil	mm			
Topography	Digital elevation model (DEM)	m	New Zealand Landcare Research	Raster	25 × 25 m
Boundaries	Territorial Authority 2016 Generalized Version	N/A	Statistics New Zealand	Vector - polygons	N/A
	NZ Area Units (2012 Yearly Pattern)	N/A	Land Environment of New Zealand (LENZ)	Vector - polygons	N/A
	Land Cover Database version 4.1 - Mainland New Zealand	N/A	New Zealand Land Cover Database (LCDB v4.1)	Vector - polygons	N/A

(*) Soil temperature regime classes include: T – thermic; WM – warm mesic; MM – mild mesic; CM – cool mesic; DM – cold mesic and C – cryic (Webb and Wilson 1995).

4.2.4. Building the dataset

The required dataset in the model contained 17 layers of fundamental variables with the same spatial resolution and coordinate system summarized in Table 4.2. All data were converted to raster-format layers with the cell size of 25×25 m. The Projected Coordinate System used in this research was *NZGD_2000_New_Zealand_Transverse_Mercator* as preferred in New Zealand. This stage was implemented by the Spatial Analyst toolbox in ArcGIS version 10.4 (ESRI, Redlands, CA, USA) and SAGA-GIS 4.2 (Conrad et al. 2015).

Table 4.2. The environmental variables of the habitat model

Variable category	Variable ID	Variable	Unit	Source
1. Climate	V1.1	Annual average temperature	°C	WorldClim Version2 (Fick and Hijmans 2017)
	V1.2	Average monthly minimum temperature of the cold season	°C	
	V1.3	Average monthly maximum temperature of the hot season	°C	
	V1.4	Precipitation	mm/year	
	V1.5	Monthly precipitation of the dry season	mm	
2. Soil	V2.1	Potential rooting depth	m	New Zealand Fundamental Soil Layers (FSLs)
	V2.2	Soil pH	<i>None</i>	
	V2.3	Soil salinity	%	
	V2.4	Soil temperature regime	As classes	
	V2.5	Profile available water in soil	mm	
3. Topography	V3.1	Elevation	m	NZ Landcare Research
	V3.2	Slope	degree	Derived from DEM (Burrough and McDonell 1998)
	V3.3	Aspect	degree	Derived from DEM (Burrough and McDonell 1998)
	V3.4	Curvature	<i>None</i>	Derived from DEM (Zeverbergen and Thorne 1987)
	V3.5	Terrain Ruggedness Index - TRI	<i>None</i>	Derived from DEM (Riley et al. 1999)
	V3.6	Topographic Wetness Index - TWI	<i>None</i>	Derived from DEM (Beven and Kirkby 1979)
	V3.7	Wind Exposition Index - WEI	<i>None</i>	Derived from DEM (Gerlitz et al. 2015)

All variable layers in three main categories were generated as follows:

Climatic layers

Climatic data were downloaded from the WorldClim database (Fick and Hijmans 2017) included:

- Monthly precipitation (mm)
- Monthly average temperature (°C)
- Monthly maximum temperature (°C)
- Monthly minimum temperature (°C)

The description of climatic seasons (i.e. hot, cold, wet and dry seasons) in New Zealand was adopted from Leathwick et al. (1998). Downloaded data were in the low spatial resolution of 30 seconds (roughly 490×490 m after conversion). From this data, the climatic variables were calculated by the tool Raster Calculator in ArcGIS 10.4 (*Spatial Analyst Tools\Map Algebra\Raster Calculator*). They are described in Table 4.3:

Table 4.3. List of climatic variables

Code	Variable	Data	Month	Calculation
V1.1	Annual average temperature (°C)	Monthly average temperature (°C)	12 months	Mean
V1.2	Average monthly minimum temperature of the cold season (°C)	Monthly minimum temperature (°C)	Jun; Jul; Aug.	Mean
V1.3	Average monthly maximum temperature of the hot season (°C)	Monthly maximum temperature (°C)	Dec; Jan; Feb.	Mean
V1.4	Precipitation (mm/year)	Monthly precipitation (mm)	12 months	Sum
V1.5	Monthly precipitation of the dry season (mm)	Monthly precipitation (mm)	Dec; Jan; Feb.	Mean

Soil layers

Soil data were downloaded from The New Zealand Fundamental Soil Layer (FSLs) (available at <https://iris.scinfo.org.nz>). This data included 05 layers as shown in Table 4.4.

Table 4.4. List of soil variables

ID	Variable	ID	Variable
V2.1	Potential rooting depth	V2.4	Soil temperature regime
V2.2	Soil pH	V2.5	Profile available water in soil
V2.3	Soil salinity		

All data were downloaded as vector layers in the projected coordinate system of NZGD_2000_New_Zealand_Transverse_Mercator and then were converted to $25 \times 25\text{m}$ raster layers by the tool *Polygon to Raster* in ArcGIS 10.4 (*\Conversion Tools\To Raster\Polygon to Raster*).

Topographic layers

As mentioned above, there were seven layers in terms of topographic variables chosen for this study, as shown in Table 4.5.

Table 4.5. List of topographic variables

Code	Variable	Code	Variable
V3.1	Elevation (meters)	V3.5	Terrain Ruggedness Index - TRI
V3.2	Slope (degrees)	V3.6	Topographic Wetness Index - TWI
V3.3	Aspect (degrees)	V3.7	Wind Exposition Index
V3.4	Curvature		

Elevation data from the digital elevation model (DEM) by Landcare Research (Barringer et al. 2002) were used. The DEM was downloaded from the public LRIS Portal (<https://lris.scinfo.org.nz/>). Other variables were derived from the DEM using various algorithms and software programs.

Slope layer was generated from the DEM by the average maximum technique, which used fundamental input as 3×3 DEM pixels. The basic algorithm used to calculate slope (in degrees) is described by Burrough and McDonell (1998):

$$\text{slope} = 57.29578 \times \text{atan} \left(\sqrt{\left[\frac{dz}{dx} \right]^2 + \left[\frac{dz}{dy} \right]^2} \right) \quad \text{Equation (2)}$$

The slope here refers to the rates of change of the elevation surface in the horizontal (dz/dx) and vertical (dz/dy) directions from the center cell (Burrough and McDonell 1998). The slope layer was created by the Slope tool in ArcGIS 10.4 (*\Spatial Analyst\Surface\Slope*).

Aspect determines the downslope direction of the highest slope value from each cell to its surroundings. Similar to the slope layer, aspect was calculated on 3×3 cell elements with a representative surface plane facing the direction of the highest slope value of the neighborhood pixels. The basic algorithm used to calculate aspect (clockwise in degree) is from Burrough and McDonell (1998):

$$\text{aspect} = 57.29578 \times \text{atan2} \left(\left[\frac{dz}{dy} \right], -\left[\frac{dz}{dx} \right] \right) \quad \text{Equation (3)}$$

This direction was calculated for the center cell that showed values clockwise in degrees from 0 (due north) to 360 (again due north as an entire circle). Flat areas (no slope direction) were classified as the value of negative 1 (ESRI 2017). The aspect layer was created by the Aspect tool in ArcGIS 10.4 (\Spatial Analyst\Surface\Aspect).

Curvature identifies the rates and directions of change of the slope over a continuous topographic surface. Curvature is defined as “the second derivative of a surface, or the slope of the slope” (Kimerling et al. 2012).

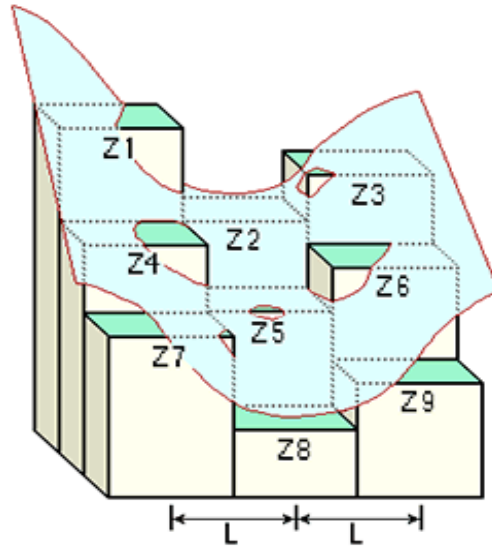


Figure 4.3. A simulation of curvature for a 9-submatrix surface (source: ESRI, 2017)

To calculate curvature for every single cell in a raster surface, Zevenbergen and Thorne (1987) simulated nine submatrix elevations (3×3 cells as in Figure 4.3) (ESRI 2017) by a partial quartic equation that was used for identifying the curvature value of the center cell in a particular altitude submatrix. The equation is (Equation 4):

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$$

The nine parameters (from A to I) have relationships with the nine submatrix elevations (from Z1 to Z9) as follows (Zevenbergen and Thorne 1987):

$$A = [(Z1 + Z3 + Z7 + Z9)/4 - (Z2 + Z4 + Z6 + Z8) / 2 + Z5]/L^4$$

$$B = [(Z1 + Z3 - Z7 - Z9) / 4 - (Z2 - Z8) / 2] / L^3$$

$$C = [(-Z1 + Z3 - Z7 + Z9) / 4 + (Z4 - Z6)] / 2 / L^3$$

$$D = [(Z4 + Z6) / 2 - Z5] / L^2$$

$$E = [(Z2 + Z8) / 2 - Z5] / L^2$$

$$F = (-Z1 + Z3 + Z7 - Z9) / 4L^2$$

$$G = (-Z4 + Z6) / 2L$$

$$H = (Z2 - Z8) / 2L$$

$$I = Z5$$

In these sub-equations, the center point is Z5 (x = 0; y = 0) and L is the cell size of the raster, as shown in Figure 4.3. As per the definition, curvature is the second derivative of the surface, so it can be calculated by the algorithm below (Zeverbergen and Thorne 1987; ESRI 2017):

$$curvature = -2(D + E) \times 100 \quad \text{Equation (5)}$$

A zero value of curvature means that the surface is definitely level. A generally convex surface has a positive curvature value at the center cell; meanwhile a negative value at that cell indicates the surface is generally concave (ESRI 2017). The curvature layer was calculated by the Curvature tool in ArcGIS 10.4 (\Spatial Analyst\Surface\Curvature).

Terrain Ruggedness Index (TRI) is a morphometric index developed by Riley et al. (1999) to quantitatively assess the heterogeneity of a topographic surface. This index, like curvature, has been significant in habitat modelling, because the heterogeneous roughness of terrain plays an irreplaceable role in a habitat, especially influencing physical flows such as water and wind that affect, both directly and indirectly, the distribution of animals in the habitat (Fabricius and Coetzee 1992). TRI can be derived from DEM, and the index of a single pixel is calculated in a focal group. The formula to compute TRI for a cell is (Riley et al. 1999):

$$TRI = \sqrt{\sum (Z_{ij} - Z_{00})^2} \quad \text{Equation (6)}$$

where Z_{ij} is the elevation of each neighbor cell to the center cell Z_{00} . The layer of TRI in this study was generated by the Terrain Ruggedness Index (TRI) tool SAGA GIS (\Geoprocessing\Terrain Analysis\Morphometry\Terrain Ruggedness Index (TRI)).

Topographic Wetness Index (TWI) is an indicator for hydrological forecasting, which combines two of the most fundamental attributes of the topographic condition controlling the hydrological processes in a habitat: “drainage area” and “slope”. This index can be calculated for a cell in a raster layer after identifying the two required attributes with respect to that cell. TWI is defined as (Beven and Kirkby 1979):

$$TWI = \ln \frac{a}{\tan b} \quad \text{Equation (7)}$$

where a is the drainage area per unit of cell size and b is the slope in radians. Drainage area here is defined as the area that collects natural precipitation and sends it through a single point. In terms of hydrology, the drainage area of a particular point Z is the area of the watershed (also catchment) that has Z as the outlet point. In addition, the slope to calculate TWI is the local slope value of the cell Z (Beven and Kirkby 1979; Moore et al. 1991). The TWI layer was computed by the Topographic Wetness Index (TWI) tool in SAGA GIS (\Geoprocessing\Terrain Analysis\Hydrology\ Topographic Wetness Index (TWI)).

Wind Exposition Index has been used for characterizing how exposed a point is to potential winds by assessing the topographic situation surrounding it. The calculation of this index is based on windward/leeward effect technique described by Bohner and Antonic (2009) in which wind effects were divided into two parameters with regard to a point of reference: windward (upwind, the wind comes to the point) and leeward (downwind, the wind leaves from the point). The two parameters windward (H_W) and leeward (H_L) are calculated by the equations below (Gerlitz et al. 2015):

$$H_W = \frac{\sum_{i=1}^n \left(\frac{1}{d_{WHi}} \times \tan^{-1} \left(\frac{d_{WZi}}{d_{WHi}} \right) \right)}{\sum_{i=1}^n \frac{1}{d_{LHi}}} + \frac{\sum_{i=1}^n \left(\frac{1}{d_{LHi}} \times \tan^{-1} \left(\frac{d_{LZi}}{d_{LHi}} \right) \right)}{\sum_{i=1}^n \frac{1}{d_{LHi}}} \quad \text{Equation (8)}$$

$$H_L = \frac{\sum_{i=1}^n \left(\frac{1}{\ln(d_{WHi})} \times \tan^{-1} \left(\frac{d_{LZi}}{d_{WHi}} \right) \right)}{\sum_{i=1}^n \frac{1}{\ln(d_{LHi})}} \quad \text{Equation (9)}$$

where d_{WHi} and d_{LHi} refer to the horizontal distances in windward and leeward directions and d_{WZi} and d_{LZi} are the corresponding elevation differences between the desirable cell and the reference cell (Gerlitz et al. 2015). The final windward/leeward index is (Gerlitz et al. 2015):

$$H = H_W \times H_L \quad \text{Equation (10)}$$

This H takes values between 0.7 for leeward and 1.3 for windward positions (Bohner and Antonic 2009; Gerlitz et al. 2015) where values below 1 indicate wind-shadowed locations; meanwhile values higher than 1 are for cells exposed to wind, all with regard to a specified wind direction. The wind exposition index (WEI) is a dimensionless index that is computed as the average of all values of H corresponding to all searching angles (from 0° to 360°) on the surface (Karger et al. 2017). This means that WEI here is the final parameter indicating the cell's exposure to winds with varying directions. In this study, the WEI layer was generated by Wind Exposition Index tool in SAGA GIS (\Geoprocessing\Terrain Analysis\Hydrology\Wind Exposition Index) with a searching distance of 30 km in angular steps of 15° from 0° to 345° in a circular sense for each raster cell.

4.2.5. Variable restriction

The ranges of the environmental variables found throughout the entire study site, generally exceeded the range for those variables in the target species' natural ranges. Potential planting sites in New Zealand should have similar environmental conditions to the current habitat of *E. bosistoana* and *E. globoidea* such that the species have a reasonable chance of surviving and providing growth and yield.

Variable restriction was a primary stage of analysis which generally restricts the potential planting sites in New Zealand to those which have similar environmental

conditions to those found in *E. bosistoana* and *E. globoidea*'s natural ranges. Variable restriction was applied in narrowing the range of each variable by excluding potential planting sites with values too far beyond those found in the natural ranges of *E. bosistoana* and *E. globoidea*. Moreover, this step also reduced computer memory usage and processing time during subsequent modelling steps.

There were diverse reasons for restricting the site availability. For example, some areas were used for land uses that were not consistent with forestry uses (e.g. residence and horticulture); the areas were in the strictly protected zone or where there was no access; especially for new PSP establishment, the areas were significantly different from the native habitat of the target species and contained adverse conditions (e.g. permanent ice or extremely low precipitation) in which the PSP establishment was unlikely to be successful.

The fundamental bases for this assessment were the environmental conditions appearing in the natural habitat, the existing trial plantations, published studies and expert knowledge in terms of the target species or the target types of forest. In addition, the expert on eucalypts gave advice on which land covers were available for trial plantations of the species in the study area. In this study, along with the land cover map adopted from New Zealand Land Cover Database (LCDB v4.1), the deterministic bases for restriction included the native habitats of *E. bosistoana* and *E. globoidea* in Southeast Australia, the existing trials by NZDFI and some public studies in respect to the tolerance of the species to adverse conditions. The two species had differences regarding their habitat conditions and existing PSPs in New Zealand. Hence, from this step (i.e. variable restriction) to the end, the process was operated for each the species individually. Moreover, an additional character, which was either "B" for *E. bosistoana* (e.g. V1.1.B and V3.7.B) or "G" for *E. globoidea* (e.g. V1.1.G and V3.7.G), was added to each variable ID to specify the variable under consideration with respect to each species.

The study obtained occurrence data of the species in their native habitat in Australia (ALA 2017). Information from 1,598 sample points of *E. bosistoana* and 12,101 sample points of *E. globoidea* were recorded. The locations of occurrences were overlaid with various available types of attribute data which were provided by The Atlas of Living Australia (ALA) and other organizations in collaboration such as WorldClim and CSIRO Ecosystem Sciences (ALA 2017).

In addition to the natural range data, there were 1095 trial sub-plots of *E. bosistoana* and 837 sub-plots of *E. globoidea* where the species were successfully planted within New Zealand. These trial plots provided additional information on the range of conditions that the species could survive in, and thus the restriction value range for each variable.

Lastly, the study referred to a number of studies on eucalypts to determine the thresholds for the species to survive. In brief, the three sources of data together contributed to determining the "recorded range" for each species, and thus the restriction thresholds.

To avoid being overly restrictive, causing loss of potential habitat area and to create chances for each species to adapt to new habitats, the recorded range was generally buffered by positive and negative 10% to create the “restriction range”.

Some exceptions to buffering the recorded range existed. The study did not apply upper limit for the restriction range of the variable *Average monthly min temperature of the cold season* as this would reduce the range, rather than expand it. In practice, this restriction range also contained values in Australia’s conditions that did not exist within the study area (i.e. New Zealand area). Hence, an interference of the restriction range in association with the range of value available in the study area was used for producing the “range of interest” of each variable restriction process is illustrated in Figure 4.4.

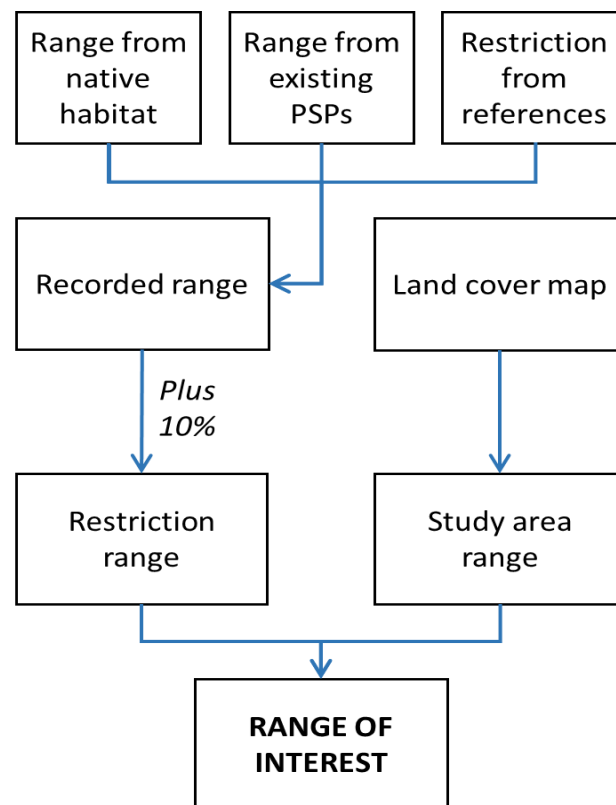


Figure 4.4. Variable restriction process

In addition, the eucalypt expert gave advice on which land covers were available for trial plantations of the target species in the study area. Once a range of interest was defined for each variable layer, all pixels with values outside the range of interest, or those with undesirable land covers, were replaced by no-data pixels, such that they would be excluded from subsequent analysis. In Table 4.6, 12 pixels with their corresponding attributes were selected randomly from the excluded areas for *E. bosistoana* as examples to demonstrate the variable restriction process. These examples show how variable restriction was used to exclude pixels with environmental characteristics unlikely to support the species.

Table 4.6. Examples of 12 excluded pixels with the reasons for their exclusion

(The X indicates which variable(s) led to the pixel being excluded)

Pixel No.	Coordinates		Model variable for <i>E. bosistoana</i>																	Land cover
	X	Y	V1.1.B	V1.2.B	V1.3.B	V1.4.B	V1.5.B	V2.1.B	V2.2.B	V2.3.B	V2.4.B	V2.5.B	V3.1.B	V3.2.B	V3.3.B	V3.4.B	V3.5.B	V3.6.B	V3.7.B	
1	2034673	5797953			X	X	X													X
2	1809248	5796366																X		
3	1910848	5790016																		X
4	1875923	5658253			X		X													X
5	1688598	5653491			X	X	X							X						X
6	1788610	5461403																		X
7	1544135	5448703			X	X	X							X						X
8	1588585	5328052	X	X	X	X	X						X							X
9	1420310	5213752				X	X													X
10	1313947	5131202	X		X	X	X													X
11	1337759	4991502		X							X									
12	1183772	4978802			X															X

4.2.6. Variable stratification

The environmental raster layers used in this study contained a large number of continuous values. Even though the full range of values for any given environmental variable were restricted by the ranges of interest, no sampling system could effectively provide sufficient samples to cover every value in those ranges. The stratified random sampling approach allows the study to improve the precision by conducting analysis on a relatively small number of groups of values instead of a wide range of continuous values.

The *range of interest* for each variable was stratified into non-overlapping strata. A stratum should include values reflecting a shared status (e.g. cold weather or uneven surface) or a particular level of characteristics of the corresponding locations (e.g. low slope or high soil pH). Defining strata requires an understanding of the range of values present within a variable, and then specifying breakpoints within the data; the breakpoints act simultaneously as an upper limit for one stratum and a lower limit for the next stratum.

Breakpoints for some of the variables used in this study were based on existing published values (Webb and Wilson 1995; Newsome et al. 2008), while others were based on an assessment of the frequency distribution of a given variable. The stratification of soil variables, slope and aspect were carried out mainly based on descriptions of New Zealand landscapes by Webb and Wilson (1995) and Newsome et al. (2008). For example, the soil pH scale was divided into six classes: very low (<4.9), low (4.9–5.4), moderately low (5.5–5.7), near neutral (5.8–6.4), moderately high (6.5–7.5) and high (>7.5).

For variables where published strata were not available, an alternative approach was required. Climatic variables and topographic variables (other than slope and aspect), were stratified following the Jenks Natural Breaks algorithm (Jenks and Caspall 1971). This stratification uses the frequency distribution of data for a particular variable and identifies natural groupings inherent in the data. Breakpoints are identified to achieve groups with similar values and to maximize the differences between strata. In this way, the variables were divided into strata whose boundaries were defined where there were relatively big differences in the data values (De Smith et al. 2015).

4.2.7. Priority index evaluation and mapping

After stratification, values of variables from existing PSP locations were collected by extracting cell values at the center points of existing sub-plot from all variable layers (i.e. raster layers). These data were recorded in the attribute table of the PSPs vector layer (point feature class). This step was implemented by the Extract multi-values tool (*Spatial Analyst Tools\Extraction\Extract multi values*) in ArcGIS 10.4. Extracted data in the attribute table of the output feature class were exported to a Microsoft Excel file (*.xlsx).

The data extracted from existing sub-plots were then assigned into strata to count the frequency of occurrence of each stratum (i.e. the number of values from existing PSPs

appearing in each stratum). The study used this frequency as an indicator for priority. The priority indicator increases with decreasing frequency in a stratum. The lower the frequency, the greater the need for new PSPs in that stratum.

The next step was to calculate a normalized priority indicator (i.e. frequency) for each stratum. This ensured that all priorities were normalized on a scale of 0 – 100, using Equation 11:

$$p_j = 100 \times (1 - f_j f_{\max}^{-1}) \quad \text{Equation (11)}$$

where p_j and f_j are the sub-priority point and the frequency of stratum j respectively and f_{\max} is the highest frequency in the variable. For example, assuming a variable was divided into three strata with the corresponding frequencies: $f_1 = 200$, $f_2 = 160$ and $f_3 = 20$. Thus, max frequency $f_{\max} = 200$ and the normalized priority for the strata were calculated following Equation (11): $p_1 = 0$, $p_2 = 20$ and $p_3 = 90$ respectively. This shows that stratum 3, with normalized priority value of 90, had the highest priority. The example demonstrated that this normalization enables a quantitative evaluation of priority in which the higher normalized priority values meant the higher priority to establish PSPs on locations with attribute values within the stratum.

After the calculation of normalized priorities for all strata in all variables, the map layers were reclassified such that every single pixel received the normalized priority value of the stratum which contained the pixel value. In other words, each map layer of a variable was converted to a priority layer that highlighted high-priority pixels on the map in respect to the particular variable.

Cartographic modelling was applied in nearly the entire procedure including processing and combining spatial data, reflecting the variables in the model to produce a final raster as the analysis result. In particular, this study used cartographic modelling as a tool to undertake standardization (i.e. calculating standardized points for priority assessment), to determine feasible areas (i.e. by excluding undesirable areas) and to produce the final priority map as the combination of all individual variables with their own weight coefficients.

As in the previously mentioned variable restriction, each variable had a range of interest and all pixels with values out of this range were replaced by no-data value as excluded from further consideration. Cartographic modelling was used to conduct an overlay following Boolean overlay, as described by Carver (1991). In this overlay, each pixel on the map was represented by a numerical vector consisting of spatially corresponding values from the model variable layers. If the vector contained at least one no-data value, it was counted as no-data and the pixel was excluded from further consideration.

The last step was to produce the map of priority index (i.e. final priority point) for each pixel within the feasible area. This index was calculated on each pixel as the weighted sum of normalized priority values from all variables by the priority function:

$$P = \sum_{i=0}^n p_i w_i \quad \text{Equation (12)}$$

where P was the priority index, n was the number of environmental variables, p_i was the sub-priority point of the variable i , and w_i was the weight coefficient of the variable i . In particular, the priority index was calculated for each pixel by a weighted sum of 17 sub-priority points regarding the 17 variables (i.e. $n = 17$). The weighted sum was done by multiplying each sub-priority layer by its weight coefficient and then summing the weighted sub-priority points on all variable grids by an algebraic overlay analysis. In this stage, the coefficient of 1.5 was used for the 04 focused variables (i.e. *annual average temperature, precipitation, soil pH* and *elevation*) and the coefficient for the rest of the variables was 1.0. With each sub-priority point having potential values of up to 100, the index could reach a maximum of 1,900.

The results of the priority index evaluation were represented by a priority index map that highlighted areas with high priority points. These areas would be identified as a target for further PSPs and trial plantations of the species.

CHAPTER 5. RESULTS

This chapter represents and discusses the results of model structure assessment before deciding on an evaluation of the priority index. The spatial distribution of available areas for the expansion of the PSP network, the evaluation process and the patterns of priority index over these areas are also discussed. This chapter is divided into four sections: (1) Model structure; (2) Available areas for the expansion of the PSP network; (3) Variable stratifications; (4) Patterns of the priority index.

5.1. Model structure

The study estimated the independence between model variables in each category to test if there were any multicollinearity problems. VIF values of all variables, which helped detect multicollinearity, are shown in Table 5.1.

Table 5.1. Results of multicollinearity analyses for the three categories of variable

Climatic variables				
Variable ID	Detection-Tolerance (%)	Coefficient of Determination (%)	Variance Inflation Factor (VIF)	Multicollinearity Present?
1.1	82.66	17.34	1.21	FALSE
1.2	76.12	23.88	1.31	FALSE
1.3	72.91	27.09	1.37	FALSE
1.4	35.50	64.50	2.82	FALSE
1.5	41.56	58.44	2.41	FALSE
Soil variables				
Variable ID	Detection-Tolerance (%)	Coefficient of Determination (%)	VIF	Multicollinearity Present?
2.1	89.90	10.10	1.11	FALSE
2.2	88.98	11.02	1.12	FALSE
2.3	96.11	3.89	1.04	FALSE
2.4	89.59	10.41	1.12	FALSE
2.5	97.64	2.36	1.02	FALSE
Topographic variables				
Variable ID	Detection-Tolerance (%)	Coefficient of Determination (%)	VIF	Multicollinearity Present?
3.1	29.29	70.71	3.41	FALSE
3.2	3.21	96.79	31.18	TRUE
3.3	54.80	45.20	1.82	FALSE
3.4	66.67	33.33	1.50	FALSE
3.5	3.20	96.80	31.24	TRUE
3.6	85.19	14.81	1.17	FALSE
3.7	42.43	57.57	2.36	FALSE

There were correlations among climatic variables when VIFs of variable 1.4 (*Precipitation*) and 1.5 (*Monthly precipitation in dry season*) were different from 1 (i.e. values of 2.8 and 2.4 respectively). However, these values were still below 5, so there was no adjustment required to the model structure in terms of climatic variables. For soil variables, there was no significant multicollinearity when the maximum VIF value was only 1.12. The problem was detected in topographic variables when VIFs of variables 3.2 (*Slope*) and 3.5 (*Terrain Ruggedness Index – TRI*) considerably exceeded 10 (i.e. approximately 31.18 and 32.24 respectively). The interpretation to the problem was that these variables had a high correlation that leads to an over-abundance of information in the model.

To solve the multicollinearity problem in topographic variables, there was a need to remove either variable 3.2 or variable 3.5 from further consideration. As a solution for this, the study would use *Slope* instead of *TRI* for priority index evaluation because *Slope* had been easier to measure/calculate and more popular in comparison with *TRI*.

To double-check whether the problem of redundant information was solved, the multicollinearity test was undertaken again for topographic variables without *Terrain Ruggedness Index*. There was no presence of significant multicollinearity, as shown in Table 5.2.

Table 5.2. Results of Multicollinearity test for topographic variables (Run 2)

Topographic variables (Run 2)				
Variable ID	Detection-Tolerance (%)	Coefficient of Determination (%)	VIF	Multicollinearity Present?
3.1	29.35	70.65	3.41	FALSE
3.2	66.44	33.56	1.51	FALSE
3.3	54.91	45.09	1.82	FALSE
3.4	84.54	15.46	1.18	FALSE
3.6	85.23	14.77	1.17	FALSE
3.7	42.80	57.20	2.34	FALSE

Hence, the priority index evaluation process would involve 16 variables other than *Terrain Ruggedness Index*. The absence of considerable multicollinearity in this model structure warranted that there were no violating variables nor any over-abundance of information in the model and each variable represented a distinct characteristics of the habitat.

5.2. Available areas for the expansion of the PSP network

The result of variable restriction was a range of interest for each variable. In general, most of the variables had their data frames narrowed except for soil pH, soil salinity and topographic aspect (Table 5.3 and Table 5.4). These smaller frames together determined the habitat conditions in which the species can survive and reproduce as the definition of habitat modelling (Fei et al. 2007; Drew et al. 2011). The reason for no change in the frames of soil pH and soil salinity was that its raw data provider (i.e. NZ Landcare Research) classified various special land covers with limited soil characteristics (e.g. coast, town, quarry, and sanctuary) as non-value areas that had already restricted the variables. On the other hand, topographic aspect might have effects on tree growth rather than affect tree mortality (NZDFI 2015) so this variable did not contribute to the restriction process.

In general, the ranges of interest for *E. bosistoana* were smaller than those of *E. globoidea*, especially for climatic variables (i.e. V1.1, V1.2 and V1.4), soil temperature regime (i.e. V2.4) and elevation (i.e. V3.1). This may be caused by the difference in ecology between the two species. According to Boland et al. (2006), *E. globoidea* has higher cold tolerance than *E. bosistoana* helping it to adapt to colder conditions and higher elevations.

Table 5.3. Results of variable restriction for E. bosistoana

Variable ID	Range from native habitat	Range from existing PSPs	From references	Recorded range	Restriction range	Study area range	Range of interest
V1.1.B	9.00–18.00	10.10–14.10		9.00–18.00	8.10–18.90	–2.55–16.79	8.10–16.79
V1.2.B	–2.0 to +8.0	0.5–5.7	No upper limit	–2.0 to 8.0	≥ -3.0	–11.93–12.2	–3.0 to +12.2
V1.3.B	22.20 –29.80	18.90–23.30		18.90–29.80	18.14–30.56	5.97–24.87	18.14–24.87
V1.4.B	636– 1916	693–1877		636–1916	508–2044	392–6807	508–2044
V1.5.B	39.0–100.0	42.0–135.0		39.0–135.0	32.9–141.1	28.0–639.0	32.9–141.1
V2.1.B	0.40–1.40	0.29–1.35		0.29–1.40	0.19–1.5	0–1.35	0.19–1.35
V2.2.B	4.0–5.0	5.2–8.0		4.0–8.0	3.9–8.1	4.7–8.0	4.7–8.0
V2.3.B	N/A	= 0.02	≤ 2.90 *	0.02–2.90	0.02–2.90	0.02–0.85	0.02–0.85
V2.4.B	N/A	CM–WM	\geq CM **	CM–T	CM–T	C–T	CM–T
V2.5.B	32.0–199.0	35.0–300.0		32.0–300.0	15.3–316.7	0–300.0	15.3– 300.0
V3.1.B	0–1196.0	15.0–640.0		0–1196.0	–119.6 to +1315.6	–60.0–3737.0	–60.0 to +1315.6
V3.2.B	0–25.57	0–33.62		0–33.62	–2.56 to +36.17	0–87.32	0–36.17
V3.3.B	1 to +359.96	–1 to 351.53		–1 to +359.96	–37.10 to +360.00	–1 to +359.94	–1 to +359.94
V3.4.B	–7.54 to +36.82	–3.84 to 7.52		–7.54 to +36.82	–11.98 to +41.26	–336.00 to +1350.40	–11.98 to +41.26
V3.6.B	1.002–15.805	7.304–16.012		1.002–16.012	0–17.492	3.377–26.421	3.377–17.492
V3.7.B	0.722–1.313	0.815–1.265		0.722–1.313	0.663–1.372	0.750–1.353	0.750–1.353

*(Webb and Wilson 1995; Grieve et al. 1999).

** (Boland et al. 1984; NZDFI 2015).

Table 5.4. Results of variable restriction for E. globoidea

Variable ID	Range from native habitat	Range from existing PSPs	From references	Recorded range	Restriction range	Study area range	Range of interest
V1.1.G	7.50–25.40	10.10–14.10		7.50–25.40	5.71–27.19	–2.55–16.79	5.71–16.79
V1.2.G	–2.7 to +17.6	0.5–5.7	No upper limit	–2.7 to +17.6	≥ -4.7	–11.93–12.2	–4.73 to +12.2
V1.3.G	20.40–32.90	18.90–23.30		18.90–32.90	17.65–34.15	5.97–24.87	17.65–24.87
V1.4.G	357–1790	693–1877		357–1877	213.7–2020.3	392.0–6807.0	392.0–2020.3
V1.5.G	39.0–100.0	44.0–135.0		39.0–135.0	32.9–141.1	28.0–639.0	32.9–141.1
V2.1.G	0.40–1.70	0.30–1.35		0.30–1.70	0.17–1.83	0–1.35	0.17–1.35
V2.2.G	4.0–6.0	5.2–8.0		4.0–8.0	3.8–8.2	4.7–8.0	4.7–8.0
V2.3.G	N/A	= 0.02	≤ 2.90 *	N/A	0.02–2.90	0.02–0.85	0.02–0.85
V2.4.G	N/A	DM–WM	\geq DM **	DM–T	DM–T	C–T	DM–T
V2.5.G	27.0–254.0	35.0–300.0		27.0–300.0	15.8–311.2	0–300.0	15.8–300.0
V3.1.G	0.0–1423.0	15.0–640.0		0.0–1423.0	142.3–1565.3	–60.0–3737.0	–60.0 to +1565.3
V3.2.G	0–26.97	0–31.12		0–31.12	2.70–33.82	0–87.32	0–33.82
V3.3.G	–1.00 to +359.95	–1.00 to +359.22		–1.00 to +359.95	37.10–396.10	–1 to +359.94	–1 to +359.94
V3.4.G	–8.12 to +41.22	–6.40 to +6.24		–8.12 to +41.22	13.05–46.15	–336.00 to +1350.40	–13.05 to +46.15
V3.6.G	0.476–16.027	6.942–16.420		0.476–16.420	0–17.975	3.377–26.421	3.377–17.975
V3.7.G	0.672–1.261	0.814–1.269		0.672–1.269	0.613–1.328	0.750–1.353	0.7506–1.3279

*(Webb and Wilson 1995; Grieve et al. 1999).

** (Boland et al. 1984; NZDFI 2015).

Areas available for the PSP network expansion (Figure 5.1 and Figure 5.2) satisfied the two main conditions that (1) all variable values in the area were within their corresponding ranges of interest; (2) the areas were in land-cover types of exotic forest or what could be replaced by plantation of exotic species (e.g. short-rotation cropland, grasslands, and exotic forest). For conservation purposes, land-cover types of park, reserve and indigenous forests were also excluded.

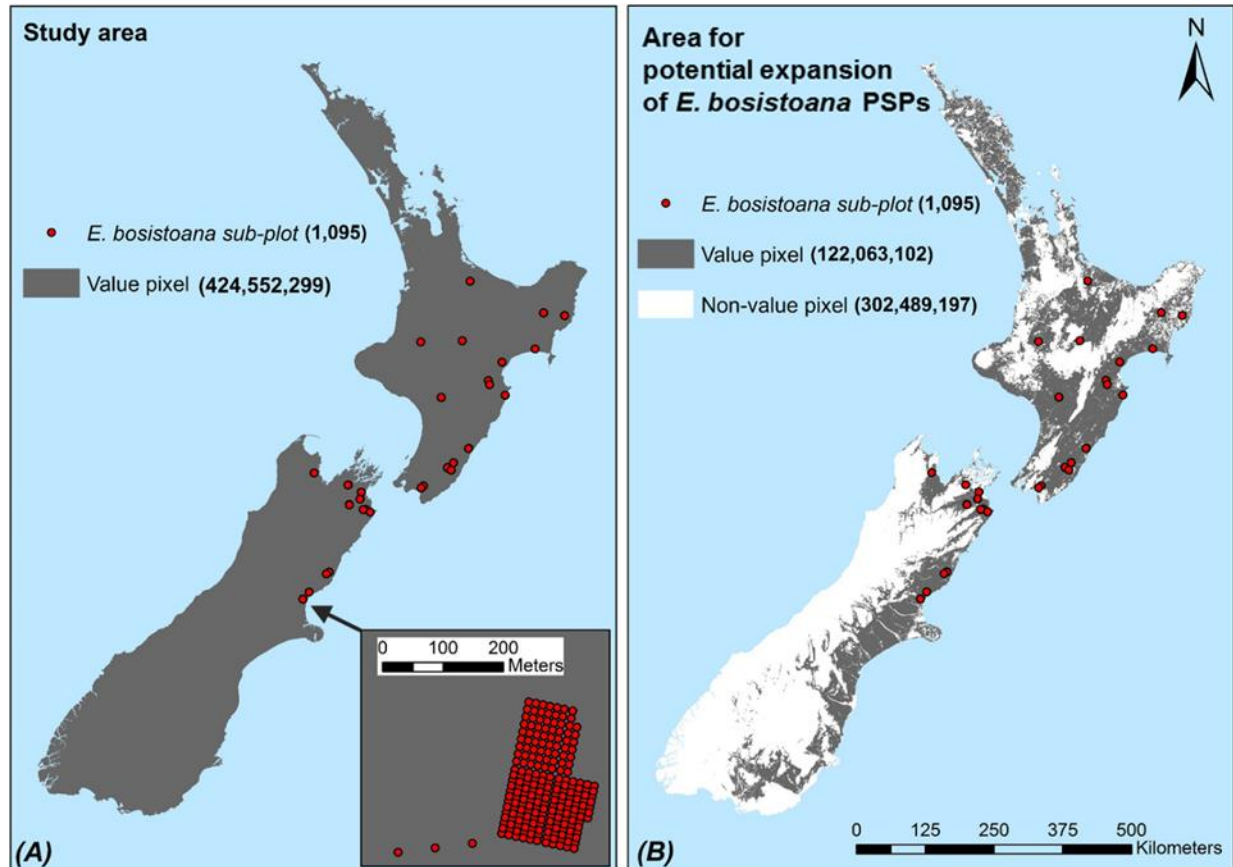


Figure 5.1. The study area BEFORE (A) and AFTER (B) variable restriction for *E. bosistoana*
(value pixel: feasible for PSP expansion; non-value pixel: excluded by variable restriction)

As shown in Figure 5.1, further PSPs of *E. bosistoana* can be established on approximately 28.75% of the study area (i.e. 76,289.4 km²). The remaining 71.25% (i.e. 302,489,197 pixels – 189,055.7 km²) was excluded, including a large natural reserve area in the North Island, high mountainous areas in the middle part, indigenous rainforests in the west part and the low-temperature areas deep to the south of the South Island.

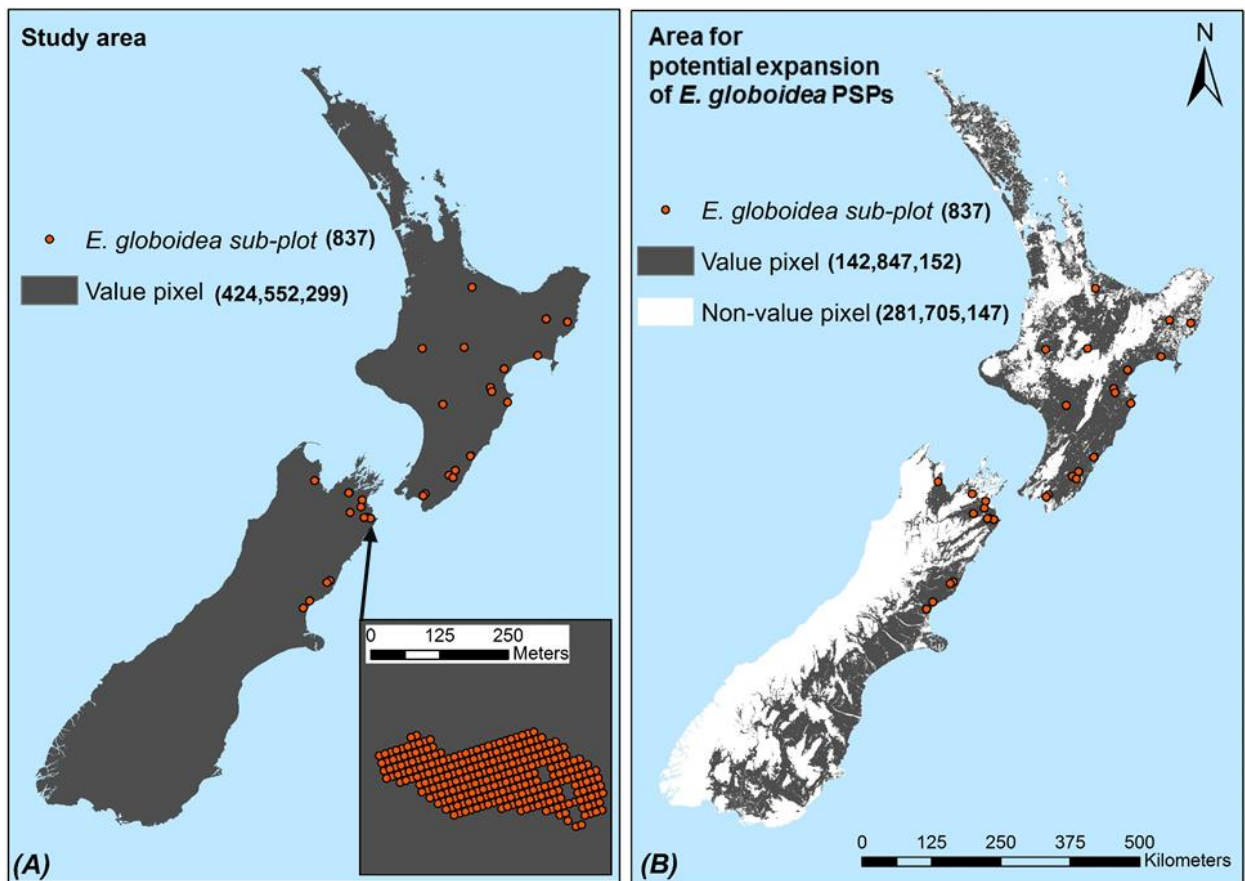


Figure 5.2. The study area *BEFORE* (A) and *AFTER* (B) variable restriction for *E. globoidea* (value pixel: feasible for PSP expansion; non-value pixel: excluded by variable restriction)

Figure 5.2 presents the result of variable restriction for *E. globoidea*, in which around two-thirds of the study area (i.e. 66.35% – 176,065.7 km²) is unavailable for the expansion of *E. globoidea* PSPs. The area for potential expansion of this species consists of 142,847,152 pixels which exceeds the figure for *E. bosistoana* (122,063,102 pixels) by roughly 17%. These extra pixels are primarily distributed at high elevation to the southwest of the South Island where is cold, and thus out of the ranges of interest for *E. bosistoana*.

5.3. Variable stratifications

The ranges of interest determined for the two species were divided into strata (Table 5.5 and Table 5.6). Comparing the stratifications in the two models for the two species, for the variables stratified following the classifications by Webb and Wilson (1995), the stratification was the same in both the models. In respect to other variables, the differences existed because of different ranges of data (i.e. these ranges had a width from below 10 to more than 1000) which were the bases for the Jenks Natural Break classification. In consequence, the compartment sizes of strata in Table 5.5 and Table 5.6 were diverse when the number of strata in each variable was up to 9.

Table 5.5. Results of variable stratification for E. bosistoana

Variable ID	Range of interest	Min. value	Breakpoint (upper limit of the stratum)									Method for stratification
			S1	S2	S3	S4	S5	S6	S7	S8	S9	
V1.1.B	8.1–16.79	8.1	8.93	9.68	10.46	11.24	12.00	12.77	13.61	14.56	16.79	Natural Breaks
V1.2.B	–3 to +12.2	–3	–1.67	–0.40	0.80	2.03	3.23	4.47	5.83	7.57	12.20	
V1.3.B	18.14–24.87	18.14	18.80	19.47	20.10	20.73	21.33	21.90	22.50	23.13	24.87	
V1.4.B	508–2044	508	730	901	1067	1225	1377	1522	1678	1850	2044	
V1.5.B	32.9–141.1	32.9	51.00	61.00	71.00	82.00	93.00	104.00	115.00	127.00	141.10	
V2.1.B	0.19–1.35	0.19	0.25	0.45	0.6	0.9	1.2	1.35				(Webb and Wilson 1995; Newsome et al. 2008)
V2.2.B	4.7–8	4.7	4.9	5.5	5.8	6.5	7.6	8.0				
V2.3.B	0.02–0.85	0.02	0.05	0.15	0.3	0.7	0.85					
V2.4.B	CM – T	CM	CM	MM	WM	T						
V2.5.B	15.3–300	15.3	30.00	60	90	150	250	300				
V3.1.B	–60 to +1315.6	–60	110.00	235.00	365.00	500.00	641.00	791.00	951.00	1125.00	1315.60	Natural Breaks
V3.2.B	0–36.17427	0	4.00	8.00	12.00	16.00	21.00	26.00	36.18			(Webb and Wilson 1995)
V3.3.B	–1 to +359.94	–1	Flat	N	NE	E	SE	S	SW	W	NW	(*)
V3.4.B	–11.976 to +41.256	–11.976	–3.52	–1.12	0.32	1.76	3.36	5.12	7.04	10.08	41.26	Natural Breaks
V3.6.B	3.377–17.492	3.377	7.25	8.06	8.87	9.77	10.76	12.02	13.46	15.17	17.50	
V3.7.B	0.7506–1.3524	0.7506	0.82	0.88	0.95	1.02	1.09	1.15	1.22	1.29	1.36	

(*) Stratified as flat surface and 8 cardinal–intercardinal directions: Flat (–1); N (0–22.5; 337.5–359.99); NE (22.5–67.5); E (67.5–112.5); SE (112.5–157.5); S (157.5–202.5); SW (202.5–247.5); W (247.5–292.5); NW (292.5–337.5).

Table 5.6. Results of variable stratification for E. globoidea

Variable ID	Range of interest	Min. value	Breakpoint (upper limit of the stratum)									Method for stratification
			S1	S2	S3	S4	S5	S6	S7	S8	S9	
V1.1.G	8.1–16.79	5.71	7.13	8.34	9.38	10.37	11.32	12.26	13.30	14.38	16.79	Natural Breaks
V1.2.G	–3 to +12.2	–4.73	–2.83	–1.30	0.13	1.43	2.73	4.00	5.43	7.23	12.20	
V1.3.G	18.14–24.87	17.65	18.37	19.07	19.77	20.43	21.07	21.70	22.30	22.97	24.87	
V1.4.G	508–2044	392	716.0	891.0	1058.0	1215.0	1366.0	1508.0	1661.0	1830.0	2020.30	
V1.5.G	32.9–141.1	32.9	51.00	61.00	71.00	82.00	93.00	104.00	115.00	127.00	141.10	
V2.1.G	0.19–1.35	0.17	0.25	0.45	0.6	0.9	1.2	1.35				(Webb and Wilson 1995; Newsome et al. 2008)
V2.2.G	4.7–8	4.7	4.9	5.5	5.8	6.5	7.6	8.0				
V2.3.G	0.02–0.85	0.02	0.05	0.15	0.3	0.7	0.85					
V2.4.G	CM–T	DM	DM	CM	MM	WM	T					
V2.5.G	15.3–300	15.8	30.00	60	90	150	250	300				
V3.1.G	–60 to +1315.6	–60	124.00	263.00	410.00	565.00	730.00	908.00	1102.00	1315.00	1565.30	Natural Breaks
V3.2.G	0–36.17427	0	4.00	8.00	12.00	16.00	21.00	26.00	33.82			(Webb and Wilson 1995)
V3.3.G	–1 to +359.94	–1	Flat	N	NE	E	SE	S	SW	W	NW	(*)
V3.4.G	–11.976 to +41.256	–13.054	–3.52	–1.12	0.32	1.76	3.36	5.12	7.04	10.08	46.16	Natural Breaks
V3.6.G	3.377–17.492	3.377	7.25	8.06	8.87	9.77	10.76	12.02	13.46	15.17	17.98	
V3.7.G	0.7506–1.3524	0.7506	0.86	0.92	0.96	1.00	1.05	1.10	1.15	1.21	1.33	

(*) Stratified as flat surface and 8 cardinal-intercardinal directions: Flat (–1); N (0 – 22.5; 337.5 – 359.99); NE (22.5 – 67.5); E (67.5 – 112.5); SE (112.5 – 157.5); S (157.5 – 202.5); SW (202.5 – 247.5); W (247.5 – 292.5); NW (292.5 – 337.5).

From the frequencies obtained by matching sub-plots' values to the corresponding strata, the sub-priority points of strata in each variable were calculated by standardization and are shown in Table 5.7 and Table 5.8. For each variable, the potential range of variation was standardized as a maximum of 100 sub-priority points. The strata covered by the existing PSPs were standardized as low sub-priority point compartments (e.g. Stratum 6 of V1.1B and Stratum 7 of V1.1G). The results in Table 5.7 and Table 5.8 presented high variations (i.e. from 0 to 100) in sub-priority points of strata in the variables, especially in wide-range variables such as elevation (i.e. V3.1B and V3.1G) and precipitation (i.e. V1.4B and V1.4G). The reason for this is that current PSPs were placed in sites with similar conditions and this PSP network has been unable to cover such wide ranges of data yet. In particular, the variable soil salinity was remarkable when all existing PSPs kept values of 0.02 and they were placed in Stratum 1. This maximized the variation of sub-priority points between strata in this variable when all other strata received 100 points of priority. In addition, the topographic aspect variable had the lowest-variation strata when the highest p_j value reached only 91 points.

Table 5.7. Frequency (*f*) and sub-priority point (*p*) of each variable stratum for *E. bosistoana*

Variable ID	Stratum 1		Stratum 2		Stratum 3		Stratum 4		Stratum 5		Stratum 6		Stratum 7		Stratum 8		Stratum 9	
	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>
V1.1.B	0	100	0	100	2	100	0	100	384	24	507	0	199	61	3	99	0	100
V1.2.B	0	100	0	100	2	99	370	2	378	0	206	46	139	63	0	100	0	100
V1.3.B	0	100	4	99	79	78	85	76	354	0	202	43	354	0	11	97	6	98
V1.4.B	273	24	359	0	276	23	156	57	16	96	2	99	8	98	3	99	2	99
V1.5.B	250	44	367	17	444	0	2	100	12	97	9	98	6	99	0	100	5	99
V2.1.B	0	100	518	0	150	71	379	27	9	98	39	92						
V2.2.B	0	100	448	9	23	95	495	0	127	74	2	100						
V2.3.B	1095	0	0	100	0	100	0	100	0	100								
V2.4.B	130	84	809	0	156	81	0	100										
V2.5.B	0	100	352	39	123	79	575	0	43	93	2	100						
V3.1.B	487	0	217	55	376	23	13	97	2	100	0	100	0	100	0	100	0	100
V3.2.B	467	0	150	68	182	61	146	69	117	75	31	93	2	100				
V3.3.B	107	57	52	79	246	0	126	49	23	91	163	34	96	61	227	8	55	78
V3.4.B	1	100	16	98	872	0	187	79	13	99	5	99	0	100	1	100	0	100
V3.5.B	577	0	383	34	131	77	2	100	2	100	0	100	0	100	0	100	0	100
V3.6.B	0	100	107	53	227	0	175	23	190	16	129	43	218	4	48	79	1	100
V3.7.B	1	100	14	97	297	26	402	0	214	47	51	87	112	72	4	99	0	100

Table 5.8. Frequency (*f*) and sub-priority point (*p*) of each variable stratum for *E. globoidea*

Variable ID	Stratum 1		Stratum 2		Stratum 3		Stratum 4		Stratum 5		Stratum 6		Stratum 7		Stratum 8		Stratum 9	
	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>	<i>f</i>	<i>p</i>
V1.1.G	0	100	0	100	0	100	2	100	3	100	263	53	564	0	5	99	0	100
V1.2.G	0	100	0	100	0	100	5	99	25	96	549	0	255	54	3	100	0	100
V1.3.G	0	100	2	99	8	97	250	16	253	15	9	97	298	0	7	98	10	97
V1.4.G	293	0	11	96	12	96	254	13	252	14	1	100	9	97	3	99	2	99
V1.5.G	290	0	250	14	265	9	3	99	10	97	8	97	5	98	1	100	5	98
V2.1.G	0	100	305	14	158	55	354	0	10	97	10	97						
V2.2.G	0	100	320	36	10	98	501	0	4	99	2	100						
V2.3.G	837	0	0	100	0	100	0	100	0	100								
V2.4.G	16	96	15	97	358	19	440	0	0	100								
V2.5.G	0	100	145	72	154	71	522	0	14	97	2	100						
V3.1.G	548	0	271	51	7	99	9	98	2	100	0	100	0	100	0	100	0	100
V3.2.G	134	46	246	0	130	47	75	70	51	79	141	43	60	76				
V3.3.G	4	99	323	14	376	0	35	91	3	99	1	100	5	99	18	95	72	81
V3.4.G	3	100	51	92	601	0	124	79	42	93	13	98	3	100	0	100	0	100
V3.5.G	345	0	227	34	177	49	82	76	6	98	0	100	0	100	0	100	0	100
V3.6.G	13	95	115	57	222	16	264	0	117	56	76	71	27	90	1	100	2	99
V3.7.G	8	96	65	70	214	0	139	35	204	5	148	31	33	85	22	90	4	98

5.4. Patterns of the priority index

The priority indices of areas for further PSPs of the two species are represented on Priority Index maps which are symbolized as values of priority index over the feasible area of the study (Figure 5.3 and Figure 5.4). The 1095 existing sub-plots of *E. bosistoana* and 837 sub-plots of *E. globoidea* were also added to the maps. It is clear that the distributions of these PSPs were across low-priority areas where they are well represented.

With 16 variables, 4 of them were calculated with weight coefficient of 1.5, the priority index can reach a potential of 1800 points. However, there was no area with such high priority that was completely under-represented by the existing PSPs with regard to all categories of environmental factors in this study. The maximum, minimum and mean of the priority index were recorded at 1,506.5, 20.5 and 750.5 respectively for *E. bosistoana* and 1666, 28.5 and 955.8 for *E. globoidea*. It is clear that the figures for *E. bosistoana* are much lower than which for *E. globoidea*. As higher priority indices indicate more needs to expand the existing plot network by establishing new PSPs at the corresponding locations (i.e. pixels), the statistical figures for the priority indices of the two species are evidence that in the current PSPs network, *E. globoidea* has stronger bias and larger gaps compared with *E. bosistoana*.

In general, high index areas were mainly in high elevation areas where the conditions in terms of the three types of variables were quite different from those in the existing PSPs. The highest priority areas for *E. bosistoana* were in Rangitikei District (i.e. Moawhango) and Taupo District (i.e. Broadlands, Rangitaiki, and Tongariro). The other relatively high priority zones included Northland and Auckland regions, the east coast of Gisborne regions, and southeast-facing hillsides of the mountain chains in the central South Island (see Figure 5.3).

On the other hand, the pattern of the index map for *E. globoidea* is slightly different. The high priority areas for this species were spread widely over the center of the North Island including Moawhango in the Rangitikei district, almost the entire area of Taupo district and its surrounding districts (i.e. except the inland water area of Lake Taupo and indigenous forests within reserve areas). The other zones of high priority index in the North Island are Northland and Auckland regions. In the South Island, the high priority index occupies almost feasible areas for the species from north to south of the island, including mountainous areas in Tasman, Marlborough and Canterbury regions, especially the entire Otago region and the east half of Southland region (see Figure 5.4).

Figure 5.3 and Figure 5.4 also indicate areas well described by the existing PSPs network of the two species (i.e. low-priority index areas). These areas include the east coast of Canterbury region, low-elevation zones in Tasman and Marlborough regions, and almost all of the Manawatu-Wanganui and Hawke's Bay regions. In particular, the network for *E. bosistoana* is superior to that for *E. globoidea* as it has covered a larger area in the regions mentioned above. These PSPs of *E. bosistoana* have also represented the environmental conditions in other regions such as Waikato, Bay of Plenty and Taranaki regions.

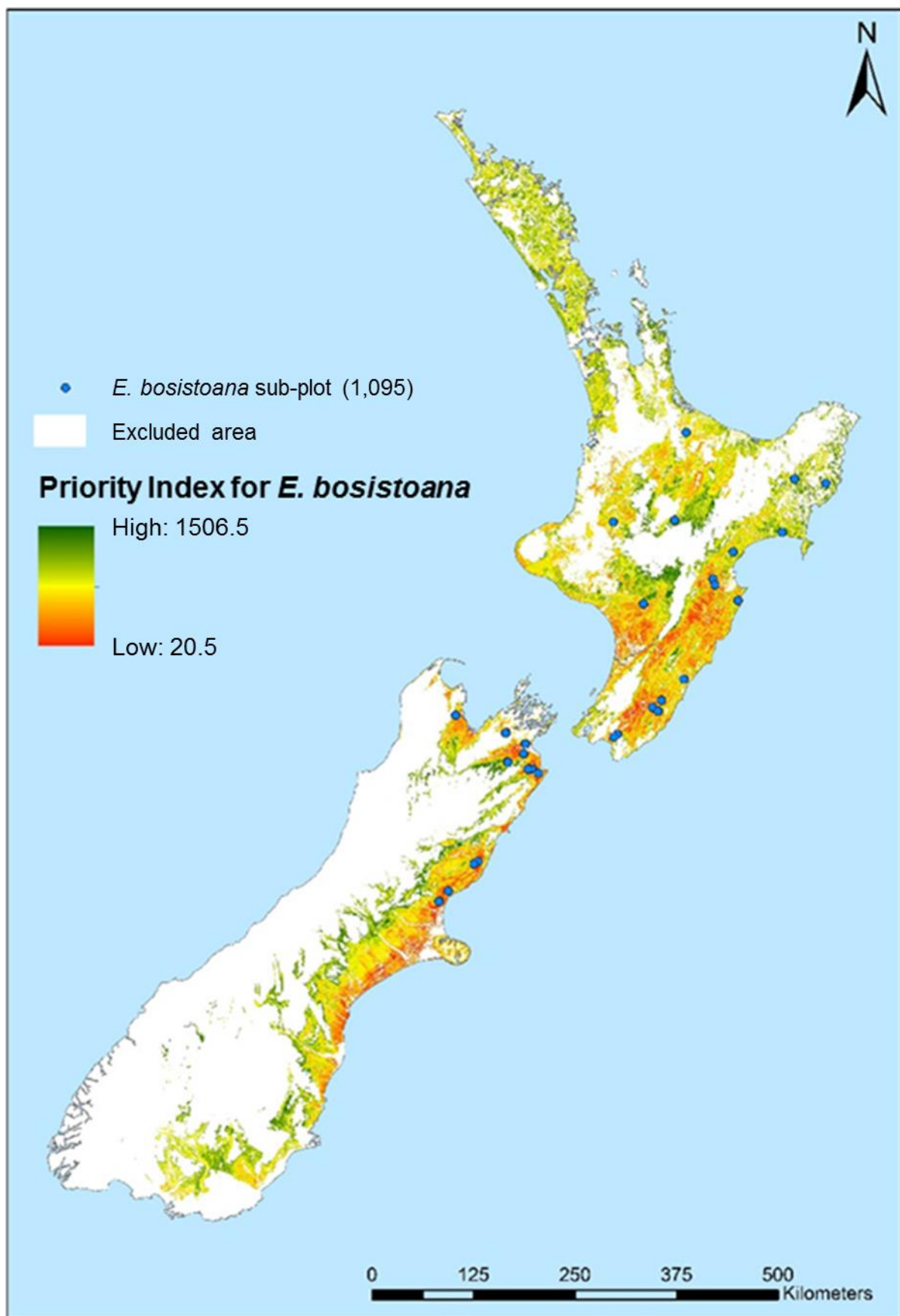


Figure 5.3. Priority Index map for *E. bosistoana*

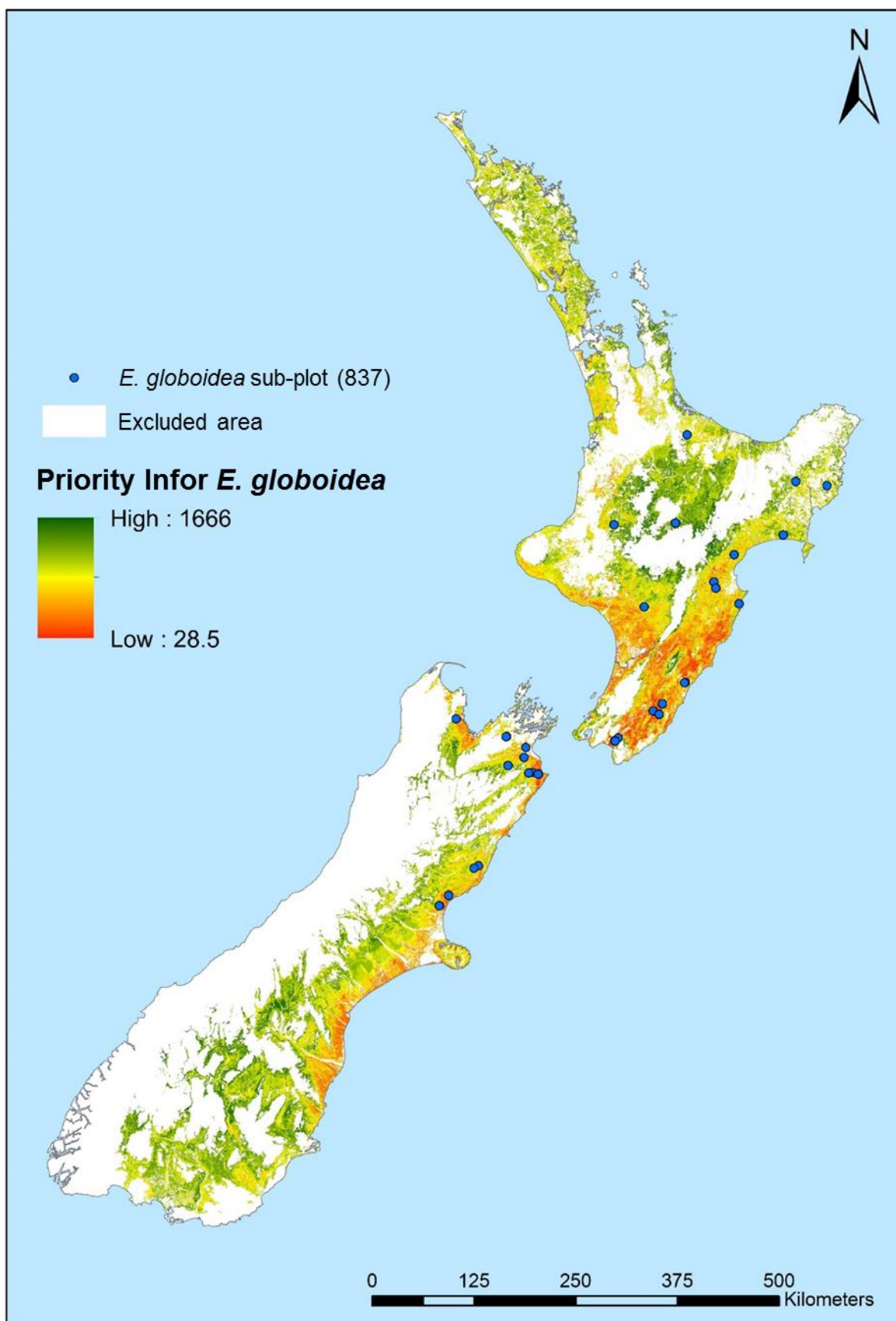


Figure 5.4. Priority Index map for *E. globoidea*

CHAPTER 6. DISCUSSION

6.1. Modelling outcomes

The results of the model successfully answered the question of the study on where we should establish new PSPs for the target species. The highlighted areas are believed to have the most potential to fill up gaps in the database of site-species interaction that has been used for the growth and yield models of the species.

In the study, I aimed to find land with environmental conditions that are different to those in existing PSPs. Indeed, new places would provide new information on the capacity of *E. bosistoana* and *E. globoides* to adapt and succeed in New Zealand's dryland environments. Following the procedure, the essence of the study was to evaluate the similarities/dissimilarities between the conditions in trial sites (i.e. where the PSPs were established) and those in the other parts of the study area feasible for eucalypt plantation. The evaluation was based on various indicators described by the model variables. Then, the levels of these similarities/dissimilarities were demonstrated by the priority index. This index increased as the similarity decreased.

In summary, the study's result is an output map representing excluded areas (i.e. not suitable for plantations of *E. bosistoana* and *E. globoides* in the study area), over-represented areas (i.e. high similarity, where the existing plots were situated and have provided significant information), and under-represented areas (i.e. high dissimilarity, where the environmental conditions have been described by no or few PSPs in the current network). Excluded areas were identified by either the native habitat conditions of the target species or the availability of land for eucalypt plantations in New Zealand. Of the remaining areas (i.e. not excluded areas), identification of over-represented and under-represented areas was based on the distribution of the existing sample plots of each species.

It was expected that low priority areas would be near the seven established sites. However, several sites were still recognized as targets for further sample plot establishments, such as the Tech Park and Lake Taupo Forest Trust sites in the North Island. The reason for this was that the priority also depended on the number of plots on each site. In these cases, a small number of PSPs existed on these sites and this was recognized as ineffective for modelling growth of plantation on a large scale such as a country (Zobel 2013; NZDFI 2015). In addition, in sites having high within-site variations (i.e. the sites contained heterogeneous conditions), the priority index was not affected by only the number of plots. In this case, this index also depended on the distribution of these PSPs over the site's area or the number of sub-plots representing particular environmental

conditions within the site. Indeed, the more plots that represent a particular environmental condition, the more well-described that condition is. The Tech Park site in Bay of Plenty region, for example, includes only three sub-plots of *E. bosistoana*. Obviously, it is impossible for all the conditions on the site to be described by only these sub-plots. Moreover, it is not possible for information to be added from PSPs in other sites to describe the environmental conditions in these sub-plots because Tech Park has its own distinct conditions, especially in terms of climate, that no PSPs in other sites can represent. Similarly, the Lake Taupo Forest Trust site in Taupo District has only two sub-plots of *E. bosistoana*, which explains why this site is in high-priority index area.

The priority evaluation procedure was applied on *E. globoidea* as well as on *E. bosistoana*. The results for the two species included two maps of the priority index. These maps followed the same trend that low priority areas were concentrated in the south of the North Island and along the east coast of the South Island (see Figure 5.3 and Figure 5.4). Also, in this trend, high priority areas for the two species included Northland and the center of the North Island, especially around Taupo District, and some high-elevation areas in south-east-facing hillsides in the middle of the South Island.

Following the same trend, the priority index patterns for the two species, however, have several differences. Firstly, the feasible area for *E. globoidea* was larger than the figure for *E. bosistoana*, including areas in Southland and the north-west half of Otago Region. This was caused by the differences between the species' native habitats. As in the analysis, the range of native habitat conditions of *E. globoidea* was wider than that of *E. bosistoana*. Indeed, *E. globoidea* has a higher cold tolerance that helps this species survive in cold conditions such as those in the northwest half of Otago Region. Secondly, in general, the priority index for *E. globoidea* is at a higher level than for the other species (i.e. larger areas of high priority index, especially in the central North Island; see Figure 5.3 and Figure 5.4). The reason for this difference is the numbers and the distributions of plantation blocks covered by the two species: in spite of being located in the same trial sites, the number of sub-plots for *E. bosistoana* is 1095, exceeding by approximately 30% as compared with the figure for *E. globoidea* of only 837 sub-plots. The larger number of sub-plots means that the conditions are described better. Moreover, uneven sub-plot distribution may lead to gaps in the PSP network and even though sub-plots of the two species might be established near/adjacent to each other, they still describe slightly different conditions due to within-site variations.

6.2. An application of GIS-based habitat modelling

The modelling procedure in this thesis follows the approach of GIS-based habitat modelling – that the habitat of a species can be described by various environmental factors.

As a result, the habitat model includes a number of variables related to the environmental factors, where each variable is formed as a GIS layer. Each location within the habitat achieves its own characterization by a set of data extracted from the variable layers. By analyzing individual variables and their combination in the model, we can aim to understand the environmental conditions existing in the habitat and use that understanding for further decision making.

Before discussing the advantages and disadvantages of the modelling application in this thesis, it is necessary to emphasize that the purpose of the application was a detection of appropriate locations for new PSP establishment, which would enhance the effectiveness of the existing PSP networks, rather than an assessment of habitat suitability for the target species. In other words, the application aimed to highlight land within the study area where environmental conditions differed most from the existing PSPs by using the priority index. In general, to describe environmental conditions in by a model, it is better to use as many variables as possible to reflect environmental conditions but there is a need to ensure each variable has its own distinction (Store and Jokimaki 2003; Drew et al. 2011). Using two or more variables with high correlations will cause bias when performing the application.

The benefits of using the GIS-based modelling technique associated with the stratified random sampling method in this case study include the ability to manage a massive amount of data, the power of spatial analysis, and the possibility of building a flexible habitat model of a huge study area. Indeed, GIS stores and converts raw data, analyzes and converts modelling data, and generates the model with maps as output. Besides raw data, modelling data, in particular, involved 17 raster layers describing the Earth's surface of more than 265,000 km²; each layer comprised of 25 × 25 m pixels. The power of GIS enabled success in managing this data. GIS was also the platform to undertake spatial analyses including the creation of derived variables, variable restriction and stratification, and cartographic modelling to generate patterns of the priority index on maps. Dealing with the huge study area, the method successfully built the priority index model without significant constraints of money, labor and time. In addition, the base of GIS provided the model with a flexibility such that model developers could easily make adjustments and modifications in modelling parameters if necessary. As a result, the model can be used for different species with different PSP networks.

Alongside those advantages, the model in this study also has disadvantages that involved some uncertain assumptions. Firstly, the methodology assumed that the data for modelling was error-free. However, there may be uncertainty in terms of data used for modelling. Errors may arise from any stage of data collection and processing. For example, this study used soil data from New Zealand Fundamental Soil Layers (FSLs). Pearse et al.

(2015) performed a statistical assessment of the FSL by comparing 208 measured observations for profile available water and potential rooting depth with those extracted from FSL. The study found that there was a weak relationship between measured observations and FSL values, and the two FSL layers considered had low accuracy. This may be due to the low spatial resolution of the FSL. The FSL layers are based on the spatial boundaries defined by the polygons in the New Zealand Land Resource Inventory (NZLRI). The NZLRI is a nationwide database comprising roughly 100,000 polygons with inconsistent areas. The consequence of this is that there is no variation in FSL soil attributes within each NZLRI polygon. In addition to this issue, there may be errors in soil measurement because of measuring instruments and in data interpolation. Despite these issues, this study had to use FSL data because it is the best nationwide dataset in existence. Such data certainties may exist in any model variable in this thesis that contradicts the error-free assumption. This led to uncertainty in the model's results and reduced the model's accuracy and precision.

Secondly, it was uncertain whether the weight coefficients used for variables in this study were appropriate. These coefficients were appointed to the variables according to expert knowledge and the focus of the NZDFI project. Indeed, the four variables with higher coefficients were proved to have played important roles in growth and yield modelling for the target species (unpublished; from expert knowledge) and so it was decided to add more weight, and thus, information for these variables to the NZDFI project's database. However, there were still questions whether there were any other variables deserved higher importance, how weighted the coefficients should be, and what the impacts of these coefficients were on the model's results. There is a need to carry out further studies answering these questions for a better application.

Thirdly, there was an assumption regarding the adaptability of the target species. Practically, each species has its own plasticity allowing it to survive in changing conditions or new conditions when introduced. In this study, there were doubts about the species' plasticities because of insufficient studies on this issue so that 10% of the habitat range was added to the determination of the range of interest to indicate the feasible area for priority index evaluation. It was controversial whether a 10% margin was appropriate, especially when considering the example of the success of *Pinus radiata* in New Zealand. The main reason for using the value of 10% was that the ranges from habitat (RH) were highly different in width between the model variables. For example, the width of RH for V2.2.B (soil pH for *E. bosistoana*) was narrow at only 1.0 meanwhile the figure for V1.4.B (precipitation for *E. bosistoana*) reached 1280. If the study used a narrow buffer for variable, such as 3%, it would be insignificant for variable with narrow RH width. The

study could not add a wide variable buffer, 25% for example, because it was likely to be impractical for variable with extremely wide width such as V1.4.B. Hence, a 10% buffer was deemed to be a reasonable compromise.

Another consideration with the model in this thesis is that a decision was made to restrict the study area to certain land covers. This restriction was necessary because it excluded areas clearly unsuitable for the target species, such as residential and estuarine areas, without considering their variable values. This step also excluded areas in indigenous forests and natural reserves, which may be suitable habitats for *E. bosistoana* and *E. globoidea*. However, in the local context, these areas were legally untouchable because of local law and policies and excluding these areas made the study's results more practicable.

In general, the methodology completely achieved the study's objectives; and the approach was successfully applied for the two different species with their corresponding existing PSPs. Although the PSP networks of the two species in this study were situated in the same model of New Zealand's habitats, the priority evaluation procedure can be applied for other study area with the availability of global environmental data (e.g. data from WorldClim Version2) and the capabilities of GIS. Indeed, there are not many constraints on creating a GIS-based description of other parts of the world following the habitat modelling approach. This means that the study innovated a new flexible habitat modelling application that has high potential to be used for different species, different PSP networks, and different study areas.

CHAPTER 7. CONCLUSION

Based on the modelling procedure, the priority evaluation, and their results, it is concluded that the study successfully built a model to identify land with under-represented environmental characteristics, when compared to those in existing PSPs for the target species. In addition, the stratified GIS-based habitat modelling approach successfully determined locations for strategic expansions of the PSP networks of *Eucalyptus bosistoana* and *Eucalyptus globoides* in New Zealand.

The results showed that the existing PSPs of the two species adequately covered the east coast of Canterbury region, low-elevation zones in Tasman and Marlborough regions, and almost all of the Manawatu-Wanganui and Hawke's Bay regions. However, the pattern of the priority index map for *E. globoides* was slightly different to that of *E. bosistoana*. The current PSP network for *E. bosistoana* was superior to that for *E. globoides* as it also represented other regions such as Waikato, Bay of Plenty and Taranaki regions. The highest priority areas for *E. bosistoana* were in Rangitikei District and Taupo District. The other relatively high priority zones included Northland and Auckland regions, the east coast of Gisborne regions, and southeast-facing hillsides of the mountain chains in the central South Island. The high priority areas for *E. globoides* were spread widely over the center of the North Island including Moawhango in the Rangitikei district, almost the entire area of Taupo district and its surrounding districts, Northland and Auckland regions, mountainous areas in Tasman, Marlborough and Canterbury regions, the entire Otago region and the east half of Southland region.

These results above have created several opportunities for future research, especially in order to eliminate the existing uncertainties in the modelling application. The first of these would be to add more variables to better describe the surrounding environment in PSPs if possible, especially in terms of soil conditions that critically influence plant's growth. This may create new challenges with respect to accurately determining the conditions in the target species' habitats. However, new environmental databases are currently being developed in New Zealand, which may be useful for future research. For example, Landcare Research's S-Map is an updated version of the FSL used in this study, that promises improved spatial resolution and the benefits that accompany it.

Secondly, it is necessary to establish trial plantings of the target species in areas with marginal environmental conditions to identify their plasticities. The models developed in this research could be re-run following new PSP establishment as establishing PSPs will result in changes to the priority index for other areas in New Zealand.

Thirdly, there should be further studies involving a statistical method for determining appropriate weight coefficients for model variables in consideration. These studies should consider the method of analytical hierarchy process (AHP), which is one of the most popular methods to obtain variables' weights in GIS-based modelling (Carver 1991; Marinoni et al. 2009; Chen et al. 2010). The effects of the weight coefficients should also be examined to contribute to the optimization of the application. This could be achieved by a sensitivity analysis that would highlight the differences between the results of models corresponding with different weighting schemes.

In this thesis, the methodology was successfully applied on two different species (i.e. *E. bosistoana* and *E. globoidea*) with their corresponding PSP networks. This methodology included a general procedure of six steps from determining model structure determination to priority index evaluation. With the general approach of GIS-based habitat modelling and the availability of globally environmental data, in spite of involving typical uncertainties that reduce the model's accuracy and precision, the new flexible application of habitat model in this study has high potential to be used for different species, different PSP networks, and different study areas.

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